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REFERENCE

Lane, B. H., 1935. Suggestions to authors of papers submitted for publication by the United States Geological Survey: U. S. Geol. Survey, Washington, D. C. (For sale by Superintendent of Documents, Washington, D. C., 25c.)

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OCTOBER 1951

MIDDLE DEVONIAN CORAL BEDS OF CENTRAL NEW YORK

WILLIAM A. OLIVER, Jr.

ABSTRACT.—Two coral biostromes in the Ludlowville formation of central New York are of special interest because of their great size and almost exclusively coral thanatocoenoses. The lower bed, designated the Staghorn Point submember of the Otisco member by Smith (1935), averages some 4 feet in thickness over an area in excess of 120 square miles, extending from Skaneateles Lake to the east edge of the Tully Quadrangle, and possibly to New Woodstock. The upper coral bed, here designated the Joshua submember, attains a thickness of 50 feet but is smaller areally, extending from Skaneateles Lake to the Tully Valley, with an area of at least 40 square miles. The faunas of these two beds differ somewhat, but both are modified derivatives of Onondaga faunas. The beds represent temporary establishment of conditions favorable for the growth of solitary rugose corals. The most important condition seems to have been the presence of a hard platform. Together with other smaller coral beds these biostromes constitute a small but significant subphase of the calcareous gray shale (*Tropidoleptus*) phase of the Hamilton group.

PREVIOUS WORK

LITTLE has been published on the Ludlowville coral beds. In the seventy or so years since the coral beds were first definitely recognized, their areal extent has been roughly worked out, their stratigraphic position determined, and some study has been made of their nature and origin, mostly as a result of the work of Dr. Burnett Smith. The Skaneateles Lake exposure has received the most attention; Smith (1912) published a paper and a few others have mentioned it as a notable locality for corals. Other outcrops of the beds have been mentioned in literature, but little attempt to trace out the beds or interrelate the known exposures has been made. Most authors have preferred to speculate on their relationship to other limestone bands. With Cooper's

(1930) work on the Hamilton group this latter point has been fairly well settled.

Amos Eaton in the second edition of his *Geological Textbook* (1832) mentioned "Corniferous limerock" outcropping along Skaneateles Lake. Although the Corniferous (Onondaga) reference was incorrect it is interesting as the first mention in literature of the coral beds. In view of this early knowledge it is surprising that both Vanuxem (1842) and Hall (1843) in their reports on the Third and Fourth Districts failed to mention them. However, Hall (1877) figured several specimens from the "Hamilton group, Skaneateles Lake," indicating definite later knowledge of this exposure.

Luther (1897, p. 282) mentioned this same exposure and two others—Lord's Hill and "along the hillside west of Otisco Lake." His correlation with the Encrinal band (Portland Point) was incorrect, however.

Cleland (1903, p. 85) in mentioning the beds, said:

> "Since in Ontario, Seneca and Cayuga counties the most abundant coral faunas are in the Basal Hamilton, either this coral reef at Skaneateles Lake is (1) a continuation of the stratum called the "Basal Hamilton," which is several hundred feet above the Marcellus shales in the Cayuga Lake section, or (2) the Encrinal, or (3) the union of (1) and (2) or (4) a separate stratum."

Since the stratigraphic position of the coral bed is in the Otisco shale member, well above the "Basal Hamilton" (Centerfield) and below the Encrinal (Portland Point) horizons, the fourth alternative is the correct one.

Clarke and Luther (1905, p. 47) mentioned the Fellows Falls exposure.

The most important study of the coral beds yet made was by Burnett Smith (1912). In his introduction he said:

> "Locally, however, we find in the shales layers which are composed of corals to the practical exclusion of other forms of life. Such layers are, in the main, of small thickness, and in studying them we are confronted with the usual limited horisontal exposure. The coral reefs (if they can be dignified with the term) which form the basis for this description are an

---

Fig. 1. Small terraces formed by the Centerfield member (C) and the platform (p). Ravines on left and right are localities 25 and 24 respectively.

Fig. 2. Portion of aerial photograph including area shown above. Terraces formed by the Centerfield (C), platform (p) and Portland Point (PP) layers are indicated. (A.A.A. Photo)

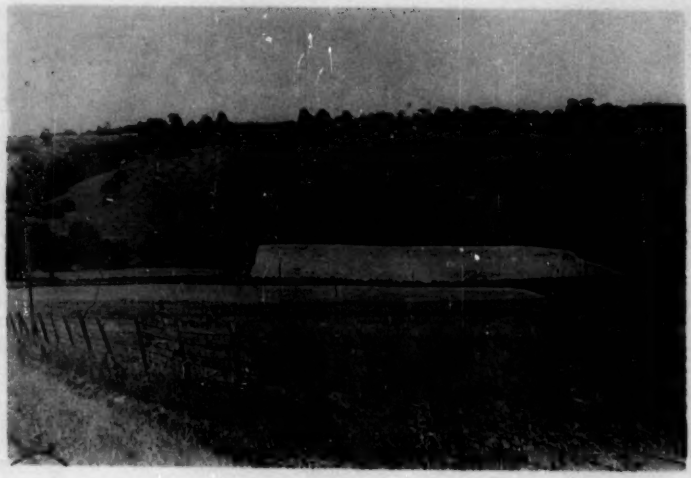


FIG. 1

FIG 2

FIG. 1

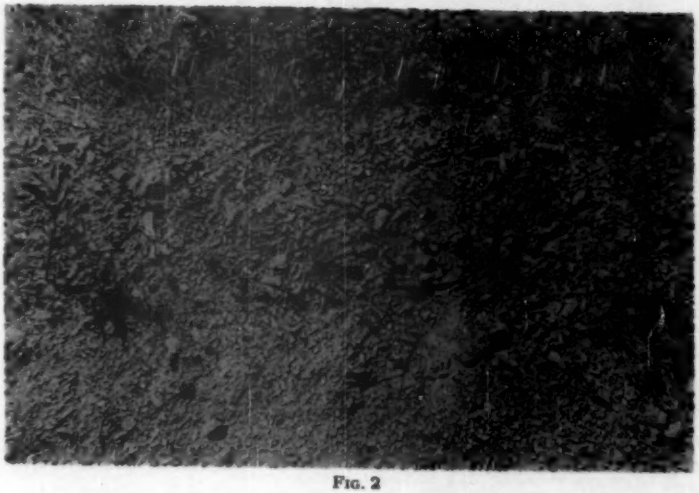


FIG. 2

> exception in this last respect, for they present a large and very beautiful exposure of about a mile along the eastern shore of Skaneateles Lake in Onondaga County, New York." (Smith, 1912, p. 446).

He divided this exposure into three parts: 1) The Large Southern Reef, 2) The Channel, and 3) The Small Northern Reef. Although these terms are useful in discussing this one exposure, they are not a strictly accurate statement of the situation. The two "reefs" may better be thought of as two western tongues of the main coral bed, the "channel" being an invagination in the western side of the bed. Smith made mention of the exposures on the west side of Otisco Lake, the Vesper (Fellows Falls) "reef" and the Joshua (Lord's Hill) exposures, and considered them to be essentially equivalent to the Staghorn Point bed. The origin of the bed was attributed by Smith (1912, p. 453) to a local clearing and shoaling of the Hamilton seas with consequent flourishing coral growth:

> "Though these changes, physical and faunal, were of short duration when compared with the whole of Hamilton time, they nevertheless represent perhaps the most striking episode in the history of the Hamilton Sea in this area, namely, a transitory return to Onondaga-like conditions, followed again by the mud-bearing waters and the mud-loving fauna of the typical Hamilton."

Cooper (1930, p. 228) described the Staghorn Point coral bed exposure as varying in thickness from one to 5 feet and extending nearly two-thirds of a mile north of where first seen, being separated by a "channel" from a small northern "reef":

> "The beds are composed mostly of cup corals, *Zaphrentis*, *Heliophyllum*, and *Cystiphyllum*, packed tightly together in a matrix of dark, sandy shale."

The Fellows Falls and Conklin's Falls exposures were mentioned.

> "East of Conklin's Falls a thin bed of corals occurs above the falls in the east branch of Limestone Creek at New Woodstock, Cazenovia Quadrangle. This has the same kind of corals and holds a stratigraphic position identical with that of the Vesper Reef." (p. 228).

Fig. 1. Surface of glacially smoothed and striated bed north of Jenney Point, Skaneateles Lake, showing natural, polished section of *Siphonophrentis*. Specimen is 4½ inches long. (Loc. 2k)

Fig. 2. Roadside exposure of Joshua submember at Lord's Hill, showing the concentration of corals which is typical of both coral beds.

An "upper reef," 65 feet thick, was mentioned as being exposed at Lord's Hill near Joshua. Luther's correlation of the beds with the "Encrinal band of the western counties" was held untenable as they are "stratigraphically below the Tichenor and Portland Point horizons, and above the Centerfield horizon."

Smith (1935, p. 46) described again the Skaneateles Quadrangle exposures of the coral beds. He included them in his Otisco member which is "the shale which lies upon the Centerfield and extends upwards for about 150 feet." (p. 45).

> "About fifty feet above the Centerfield occurs the lower coral bed with the hard and coarsely bedded platform on which it rests. The latter is transitional from softer shale below and ranges between five and ten feet in thickness. Its capping coral bed or 'reef' is commonly about three or three and one-half feet thick but may thin down to almost nothing."

The Staghorn Point exposure was mentioned, and the name Staghorn Point submember proposed for the "coral bed or reef typically shown just south of Staghorn Point." Exposures along Otisco Lake valley were mentioned and it was suggested "that a reef margin trending a few degrees east of north is indicated for the Staghorn Point submember in the belt between Skaneateles Lake and the eastern wall of the Otisco Lake valley." Exposures at Otisco Valley hamlet and Fellows Falls in the Tully Quadrangle were mentioned. The upper coral bed was described as being 90 feet above the Centerfield, with a maximum thickness of "somewhat over 30 feet," on the west side of Otisco Lake. The exposure of this bed in Tenmile Point ravine was mentioned, but no details were given. No discussion of the origin of the beds was included, reference being made to the author's earlier work (Smith, 1912).

Wells (1937) discussed in detail the "Individual variations in *Heliophyllum halli* Edwards and Haime found in the coral beds." He summarized the previous work done on the coral beds by enumerating the described localities, giving thicknesses and stratigraphic position where indicated by the earlier workers. A list of the coral species identified by him was included. A summary of Smith's interpretation of the beds (Smith, 1912, p. 453) was made and expanded upon:

> "Most of the corals listed above were related to, if not identical with, those of the Onondaga limestone of lower middle Devonian

> age which had scattered at the close of that epoch in New York. Returning once more in the early Ludlowville, they remained more or less abundant until the end of Tully time." (Wells, 1937, p. 6).

Cooper and Warthin (1942, p. 887) mentioned the lower coral bed in connection with their discussion of the Centerfield limestone fauna. They suggested that from the faunal point of view the lower coral bed "may belong to the Centerfield," pointing out that the Centerfield fauna continues up through the lower shales of the Otisco member.

There are a few other references to the Ludlowville coral beds, but they consist merely of brief mention of the beds as fossil collecting localities. They are indicated in the reference list by an asterisk(*).

ACKNOWLEDGMENTS

The writer wishes to express appreciation to Professor J. W. Wells of Cornell University for guidance and assistance in this work. Professor C. M. Nevin criticized the manuscript and gave several suggestions regarding the diagrams. Thanks are due Mrs. Mary H. Ross whose recent study of the tabulate corals of the New York Hamilton beds was important in paleoecological interpretation.

Field work in the summer of 1949 was aided by a grant from the New York State Science Service, for which grateful acknowledgment is here made. The work was done at Cornell University as partial fulfillment of requirements for the M. A. degree, June 1950.

SETTING OF THE CORAL BEDS

The general stratigraphic setting of the area under discussion is indicated in figure 1. The Otisco member of the Ludlowville formation includes the two main coral beds. This member is composed of very fossiliferous thin-bedded, gray shale, bounded below by the resistant, more massive argillaceous limestone of the Centerfield member and above by the harder and thicker-bedded shales of the Ivy Point member.

The positions of the beds vary somewhat (fig. 3) but in general they are about 50 and 95 feet respectively above the top of the Centerfield. Because of their position above the Centerfield limestone and well below the Portland Point horizon (fig. 1), the suggested correlations of Luther (1897,

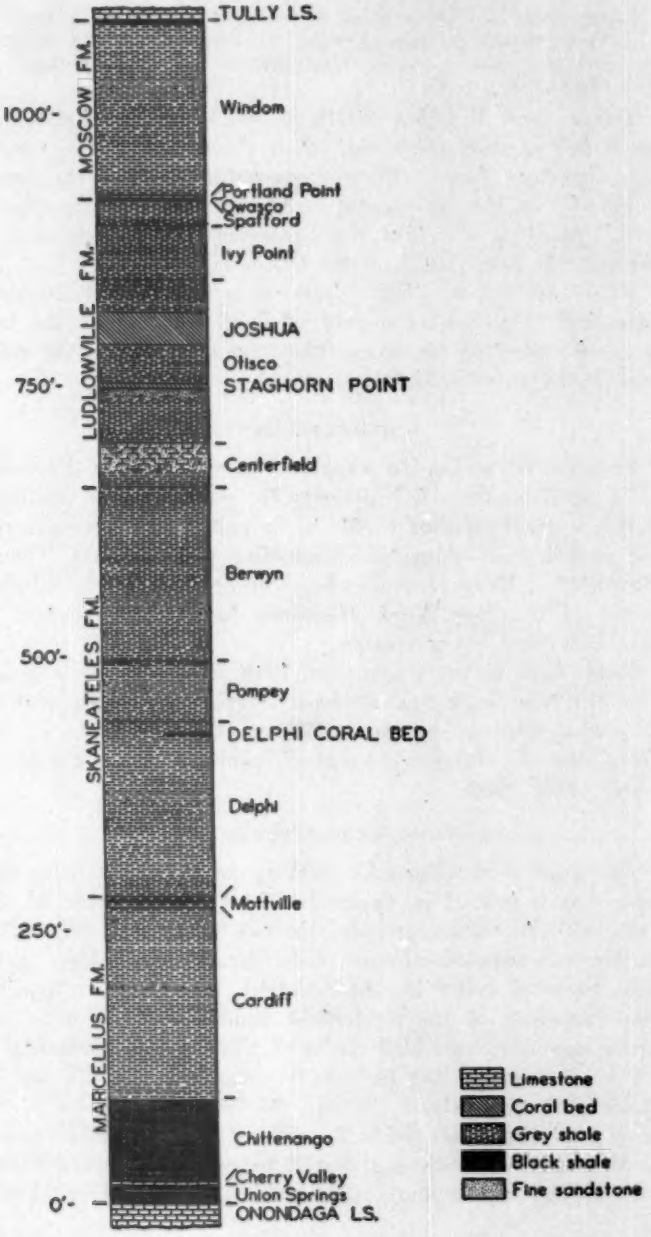


Fig. 1. Generalized Hamilton section for the Tully quadrangle. (Data from Cooper, 1930 and Smith, 1935).

p. 282) and Cleland (1903, p. 85) with the "Basal Hamilton" (Centerfield) or with the "Encrinal" (Portland Point) are not possible. No limestone bands are known from the Otisco shale or its equivalents either east or west of the area described in this paper, and the coral beds thus form distinct units within the Otisco.

The coral beds themselves consist of a mass of rugose coral skeletons so numerous and closely packed that only the interstices are filled with a matrix of the same shaly sediment which constitutes the body of the Otisco member (plate 2, fig. 2). Individual corals vary in length from one to as much as 24 inches. Most of the corals appear to have been turned over and rolled, but some are seen in their positions of growth. Colonial rugose corals are uncommon, except locally as noted below, but together with the equally scarce tabulates are found in their living positions. The faunas of the two beds differ in detail (table 1), but both are characterized by a great profusion of rugose corals and a relative scarcity of tabulate corals. Notable is the almost complete absence of other groups such as bryozoa, brachiopods, molluscs, crinoidal fragments and trilobites which are abundant in the Otisco shale proper.

The lateral relationships of the two beds are similar (figs. 3, 4 and 6). The greatest thickness of each bed is found centrally while toward the edges a gradual thinning is noted. At the extreme edge the beds interfinger with the surrounding shale. Occasional shale lenses or tongues are found more centrally located, indicating periods when the corals were locally overwhelmed by the muds.

The upper and lower contacts of the beds are sharply defined except in the fringing areas where there may be a complete gradation up into the normal shales. Of interest is the presence of a basal platform which forms the substrate on which the first corals grew. Later corals grew on the skeletons of their predecessors. The platforms were of the utmost importance in determining the areal distribution of the coral beds, only the thin, interfingering, lateral stringers of corals extending beyond their limits.

Over most of the area covered by the coral beds, the structure is relatively simple, the main feature being the gentle regional dip which averages about 50 feet per mile in a direc-

TABLE 1

Relative Abundances of the Rugose Species in the Joshua and Staghorn Point Coral Beds.*

	Joshua	Staghorn Point
Siphonophrentis halli E. and H.	◯	◯
Cystiphylloides americanum E. and H.	◯	◯
Cystiphylloides conifollis Hall	○	○
Bethanyphyllum robustum Hall	○	○
Heliophyllum halli E. and H.	○	○
Eridophyllum subcaespitosum Nicholson **	○	○
Heterophrentis simplex Hall	○	∘
Cystiphylloides corrugatum Hall	○	○
Cystiphylloides varians Hall	○	○
Heterophrentis ampla Hall	○	○
Heliophyllum confluens Hall	∘	•
Heliophyllum sp. nov.	∘	
Hexagonaria prisma Lang and Smith	∘	
Stereocelasma rectum Hall	∘	∘
Bethanyphyllum galerum Hall	∘	
Amplexiphyllum hamiltoniae Hall		∘

*Area of circle indicates relative abundances.
**Based on colonies, not individuals.

tion slightly west of south. This inclination causes the lower bed to dip out of sight to the south while both beds rise above the present erosion surface to the north, leaving little information on the original extent of the beds in those directions. Marked thinning of the lower bed toward the south, however, suggests the proximity of the edge of the bed in that direction (fig. 3).

One fault zone is worthy of mention because of its effect on the outcrop at Lord's Hill. It can be traced for a distance of 2 miles and has a maximum observable displacement of 46 feet. The fault plane strikes N 57° W and is almost vertical. The situation in the ravine at Lord's Hill (Loc. 41) is shown in figure 5. One-half mile southeast in another ravine (Loc. 40) the displacement is again observed. Here however the fault (or fault zone) passes between the lower bed and the Centerfield horizon, causing the vertical interval between the two to be some 40 feet greater than usual. In a third ravine at Case Hill (Loc. 39) in line with the other two localities, a 5-foot displacement is seen within the upper bed. This fault can not be traced west of the first ravine noted because of the jointed nature of the shales, but it certainly extends as far as the road exposure at Lord's Hill (Loc. 42) where it probably is responsible for the excessive thickness of the upper bed at that locality.

THE LOWER CORAL BED
(STAGHORN POINT SUBMEMBER)

The lower coral bed, designated the Staghorn Point submember by Smith (1935, p. 46) from the exposures north and south of Staghorn Point on the east side of Skaneateles Lake, is in the Otisco shale about 50 feet above the top of the Centerfield limestone (fig. 1). The position of the bed with the Centerfield as datum varies regularly, being slightly higher to the north and west than it is to the south and east.

The Staghorn Point bed can be traced in an east-west direction for a distance in excess of 15 miles, from Skaneateles Lake to the east edge of the Tully Quadrangle (fig. 2). On the west side of Skaneateles Lake (Loc. 1), at the proper horizon is found a very thin zone of the same corals which characterize the Staghorn Point exposure on the opposite side of the lake. This zone probably represents the western

or northwestern feather edge of the bed. The northwestern extremities of the bed are seen along the east side of Skaneateles and along Otisco Lake. Farther east the northern limits of the bed are indeterminable for reasons cited above. The southern limits are likewise unknown except in the Otisco Valley where the southernmost exposures (Loc. 7) show a marked thinning of the bed in that direction (fig. 6.).

The eastward extent is not precisely determinable, since good sections are infrequent east of Butternut Creek Valley. The more easterly exposures are of limited value, indicating only the presence of the bed. Cooper (1930, p. 223) mentions a "thin bed of corals . . . above the falls in the east branch of Limestone Creek at New Woodstock, Cazenovia Quadrangle," having "the same kinds of corals and . . . a stratigraphic position identical" with that of the lower bed. Unfortunately, since Cooper did his work, a dam has been built at this site so that it is no longer possible to see the coral bed. Further, no other bedrock exposures at the proper horizon have been found in that area and structure projections from the known position of the bed would place it some 50 feet higher than Cooper's horizon, perhaps indicating that his bed is Centerfield in age. But assuming Cooper's identification to be correct, the coral bed is thus extended an additional 7 miles eastward. Exposures of the Otisco shale near Erieville, 5 miles farther east, indicate that the coral bed does not extend that far.

The thickness of the lower bed ranges from a few inches in the fringing areas to almost 12 feet at Conklin's Falls. There is no regular pattern of variation except at the extremities where it thins down to feather edges. The variation in thickness of the lower bed is indicated in figures 3, 4 and 6.

The commonest genera found in the Staghorn Point submember are *Siphonophrentis*, *Cystiphylloides*, *Heliophyllum*, *Heterophrentis*, *Bethanyphyllum* and *Eridophyllum*, in that order. *Stereolasma*, common in the surrounding shales, is found only in the shaly or interfingering edges of the coral bed. *Favosites* is rather widespread, but specimens are comparatively scarce. A single stromatoporoid has been found. Tables 1 and 2 show the relative abundances of the rugose corals identified by the writer and their lateral distribution. In addition the following tabulates have been identified by Mrs. Mary Ross:

Aulopora elleri Fenton
Aulopora sp.
Ceratopora jacksoni Grabau
Favosites arbuscula n. subsp.
F. emmonsi Rominger
F. two new species
F. turbinata Billings

All of these are flat and expanded or branching in form.

TABLE 2

Lateral Distribution of the Rugose Species in the Staghorn Point Submember.

	Feather edge	Shaly edge	Edge of main body	Main body
Stereoelasma rectum Hall	X	X		
Cystiphylloides varians Hall	X	X		
Cystiphylloides conifollis Hall	X	X	X	X
Siphonophrentis halli E. and H.	X	X	X	X
Heliophyllum halli E. and H.	X	X	X	X
Amplexiphyllum hamiltoniae Hall		X		
Bethanyphyllum robustum Hall		X	X	
Heterophrentis simplex Hall			X	
Eridophyllum subcaespitosum Nicholson			X	X
Heterophrentis ampla Hall			X	X
Cystiphylloides americanum E. and H.			X	X
Cystiphylloides corrugatum Hall			X	X
Heliophyllum confluens Hall				X

Over most of its area the lower coral bed rests on a hard platform of ripple-marked silty sandstone, which grades downward within 5 or 10 feet to the shale of the Otisco member. This platform produces a small waterfall in almost every ravine which cuts across it. In addition it forms a small but prominent escarpment along the valley sides, at places being visible from a distance of one or 2 miles (plate 1). The coral bed is much less resistant to weathering and erosion than the platform, and is only exposed where ravines or gullies cut deeply across the platform. In some localities, even in steep ravines, the coral bed may be completely covered, its presence being indicated only by a concentration of corals and pieces of coral bed, on and just below the platform.

The lateral relationship between the coral bed and the shale

is exceptionally well known in the cliffs along the east side of Skaneateles Lake where the Staghorn Point bed is exposed with very few interruptions for a mile and a half. This section is shown in detail in figure 4. The northern part of this exposure shows the interfingering and shaly character of the edge of the bed. Just north of Jenney Point (Loc. 2k), what is apparently the lowermost of the fanning beds shows glacial striae on its upper surface and is overlain by glacial till, indicating that part of the fanning zone has been removed (plate 2, fig. 1).

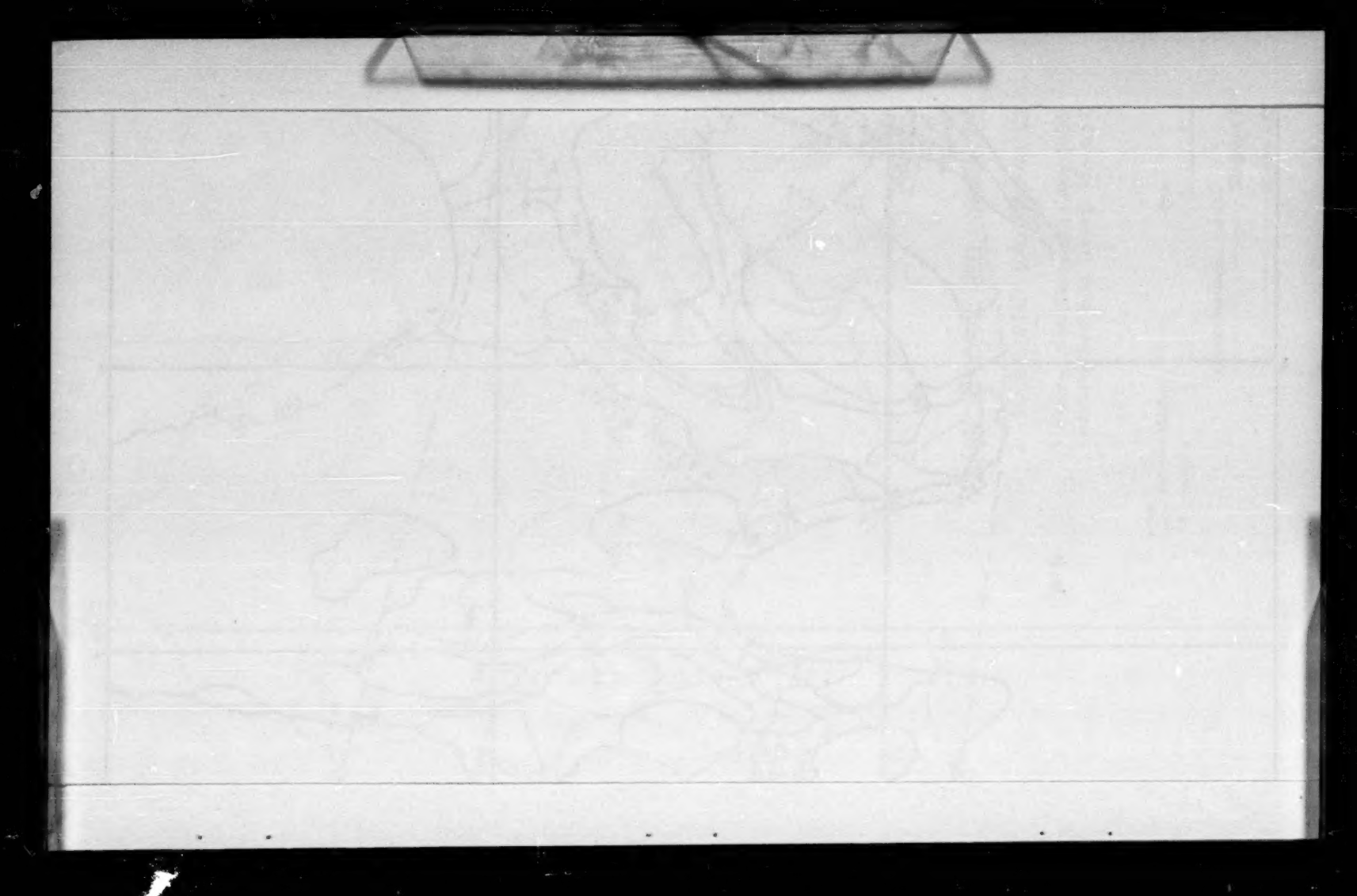
THE UPPER CORAL BED (JOSHUA SUBMEMBER)

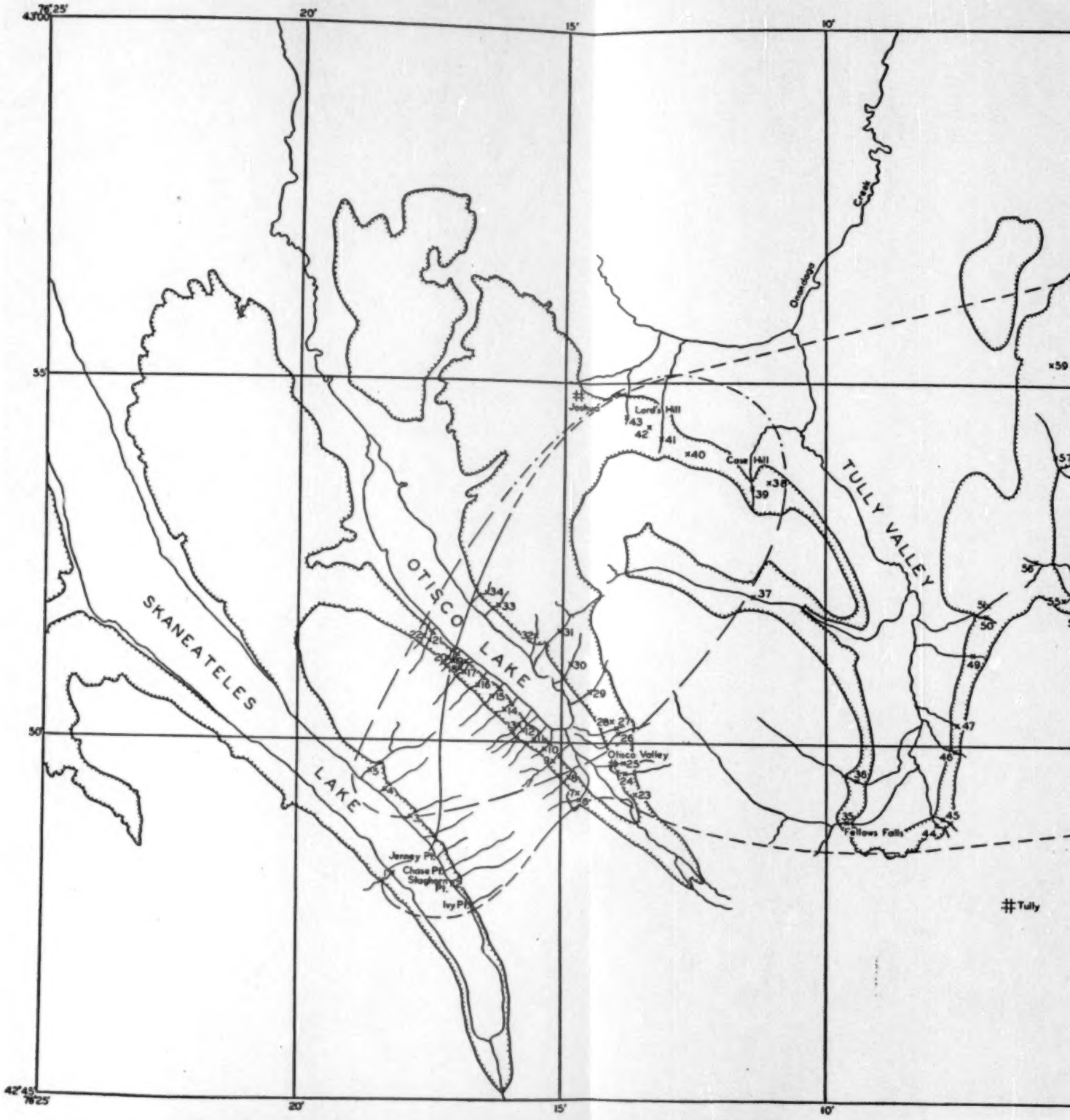
The upper coral bed is here designated the Joshua submember of the Otisco shale from the exposures at Lord's Hill near Joshua (Locs. 40 and 41). The interval between the coral bed and the Centerfield limestone varies regularly from 90 feet in the southern area to 100 feet in the more northern type area.

Smith (1935, p. 47) recognized the upper coral bed as a unit separate from the lower bed. In his earlier work (1912, p. 452) he had recognized that the Joshua exposure was at a much greater elevation, but thought that the regional dip was responsible and that the two beds could be stratigraphic equivalents.

The upper coral bed has a northeast-southwest extent of nearly 9 miles from the east side of Skaneateles Lake to Case Hill in the Tully Valley. The areal extent of this bed (fig. 2) is better known than that of the lower coral bed. Only in the area north and northwest of Lord's Hill where the coral bed horizon has risen above the present ground surface are the limits uncertain. Although the area covered by the upper bed is small compared to that of the lower bed, the thickness is much greater, as indicated by figure 3. The excessive thickness of 65 feet, however, mentioned in literature for the Lord's Hill road cut exposure (Loc. 42) is probably due to faulting as previously noted. The actual maximum of about 50 feet is found on the east side of Otisco Lake and in the type section. Laterally the bed thins and is marked at its edges by thin fingers extending into the shale (fig. 6).

The rugose genera found in the Joshua submember are




76°25'
20'
15'
10'
43°00'
55'
50'
42°45'
SKANEATELES LAKE
OTISCO LAKE
TULLY VALLEY
Onondaga Creek
Jordan
Lord's Hill
Case Hill
Otisco Valley
Fellows Falls
Jersey Pt.
Chase Pt.
Ivy Pt.
Tully

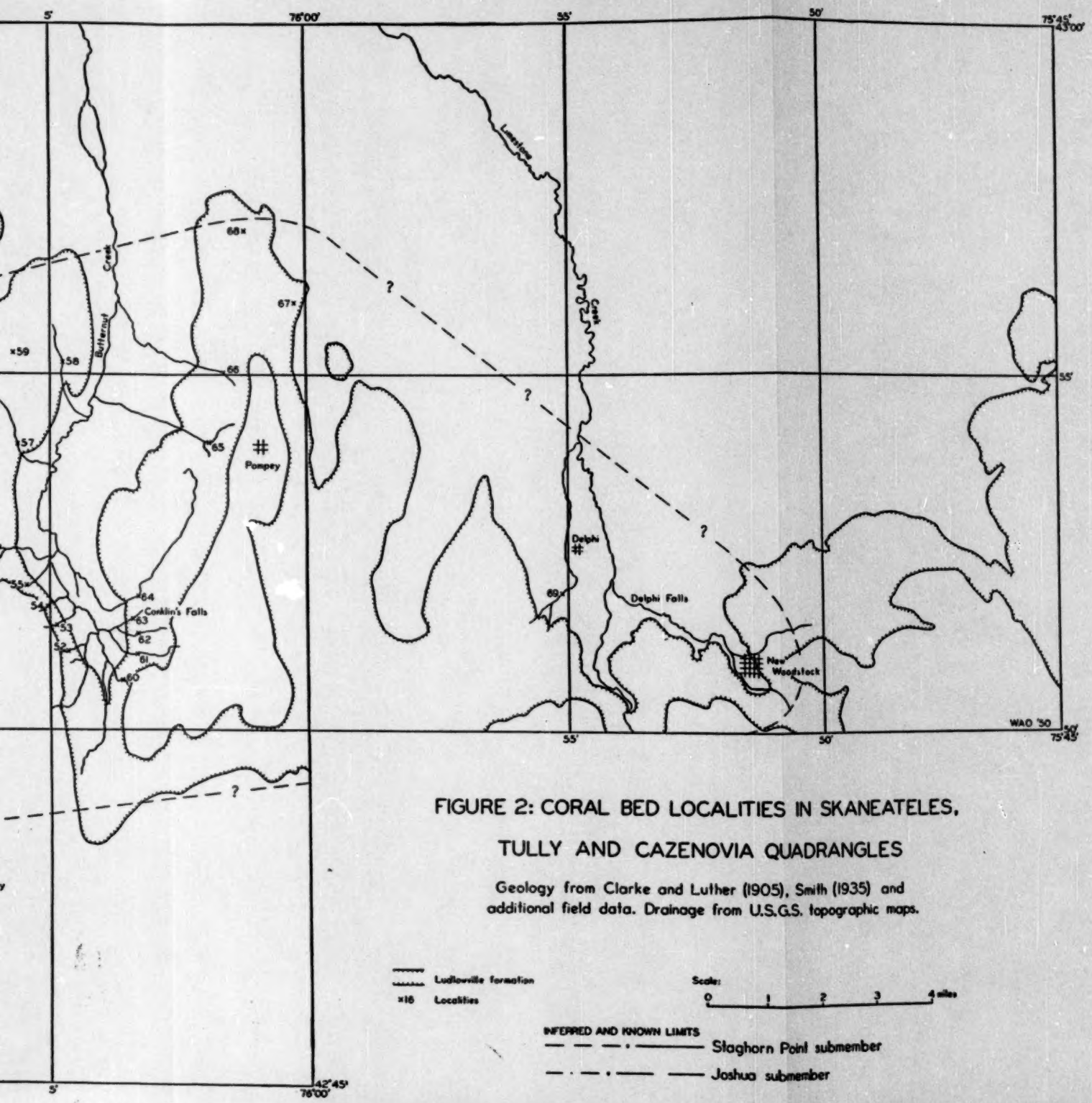


FIGURE 2: CORAL BED LOCALITIES IN SKANEATELES, TULLY AND CAZENOVIA QUADRANGLES

Geology from Clarke and Luther (1905), Smith (1935) and additional field data. Drainage from U.S.G.S. topographic maps.

Ludlowville formation

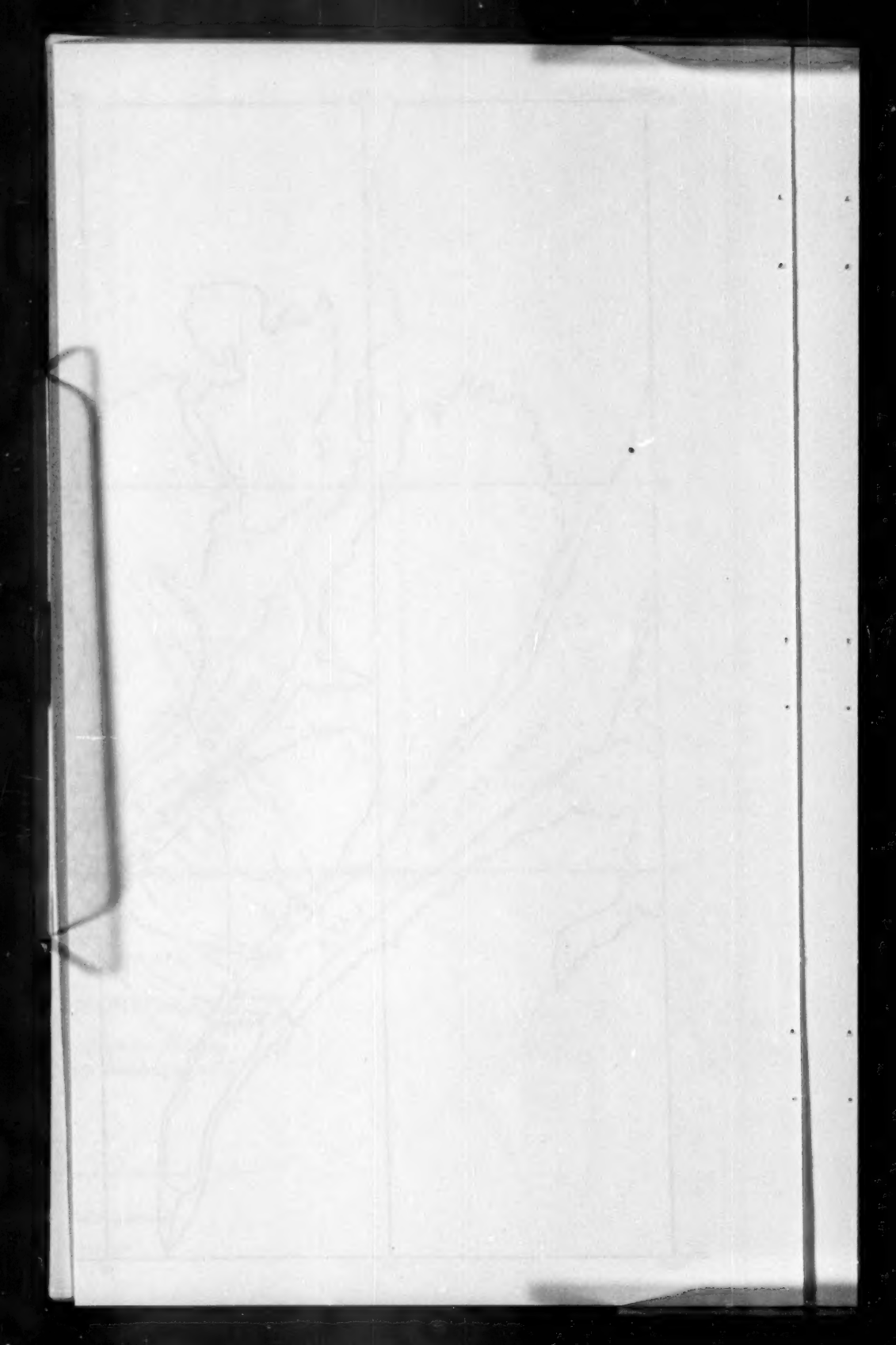
×16 Localities

Scale: 0 1 2 3 4 miles

INFERRED AND KNOWN LIMITS

Staghorn Point submember

Joshua submember



the same as those found in the lower bed, but they differ in abundance. The most common genera are *Cystiphylloides*, *Siphonophrentis*, *Bethanyphyllum*, *Heliophyllum* and *Heterophrentis*, in that order. *Heliophyllum* is not as common as in the lower bed and *Bethanyphyllum* and *Cystiphylloides* are more so. The colonial rugose form *Eridophyllum* is found irregularly distributed throughout the main part of the coral bed as in the lower one, and in addition forms a basal zone from 6 to 12 inches thick over most of the area covered by the bed. Table 1 shows the relative abundance of the rugose species in the bed. Mrs. Mary Ross has identified the following tabulates:

Favosites placenta n. subsp.
F. alpensis n. subsp.
F. wartheni n. subsp.

These are thick massive forms, some with knobby surfaces. None are delicate, branching forms.

The base of the upper coral bed lies in sharp contact on the shale of the Otisco member, with no sandstone platform. But at almost every exposure of the bed where the lower contact can be seen, there is the basal *Eridophyllum* zone. These colonial rugose corals probably colonized the area during an interval of favorable conditions and formed a crude platform on which the solitary corals grew.

OTHER HAMILTON CORAL BEDS

Although the two coral beds described in this paper are unusual because of their thickness, extent and almost exclusively coral composition, they are not unique, and many smaller coral beds have been reported from the Hamilton of New York and adjacent areas of Pennsylvania and Ontario. Two of these occurrences have been visited and another coral bed was found during the course of the present work. These and a few others will be discussed briefly to enlarge the general picture of the occurrences of coral beds and the environmental factors favorable for their development.

Meristella-Coral Zone.—This coral bed located in the basal part of the Otsego member of the Marcellus formation in eastern New York was named by Cooper (1934, p. 549) who mentioned two localities where the zone could be recognized. At one of the localities—Stony Creek, one mile south-

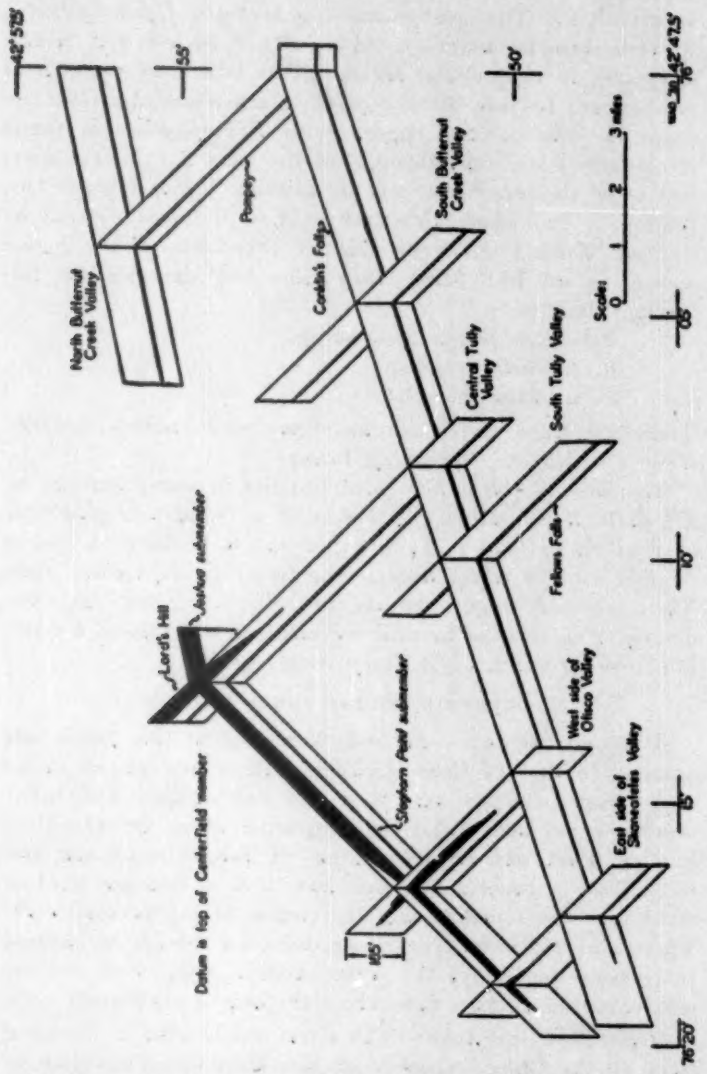


Fig. 3. Fence diagram, spatial relations of Ludlowville coral beds, central New York.

east of Middleburg, Schoharie Quadrangle—corals are rare. At the other locality—one and one-half miles southwest of East Berne, Berne Quadrangle—corals are abundant. Goldring (1935, p. 190) describes the bed in the latter locality as "a three foot coral bed, the lower two feet of which are calcareous and the upper one foot the main coral zone. '*Zaphrentis*', *Cystiphyllum*, several tabulate corals and representatives of other groups, brachiopods especially, form the principal faunal elements." Very little can be added to this description. The lower 2 feet of the zone is the upper part of a very hard, sandy layer, in which collecting is extremely difficult. The upper foot is shaly and corals, principally *Siphonophrentis* and *Cystiphylloides*, are easily extracted.

This bed differs from the Ludlowville beds in many ways. The corals seem to be concentrated in the middle part of the bed, becoming more sparse as the upper and lower limits of the bed are approached. As mentioned above, other animal groups, especially the brachiopods, are important constituents of the transition zones, although the middle part of the bed seems to be almost exclusively formed by corals. The areal extent of the zone is not known, although the fact that Cooper's two localities are some 15 miles apart indicates that it may not be inconsiderable. The Stony Creek occurrence, however, can hardly be called a coral "bed," and the extent of the true coral bed may not be very great.

Delphi Coral Bed, Skaneateles Formation.—A thin bed of zaphrentid corals was found in the upper part of the Delphi member of the Skaneateles formation, approximately three-quarters of a mile southwest of Delphi, Cazenovia Quadrangle (Loc. 69). The bed, which is only 6 inches thick, is in the midst of the "coarse sandy shales and sandstones abounding in pelecypods, which form the bulk of the fauna," described by Cooper (1930, p. 220) from the Delphi Falls section. It is tightly packed with individuals of *Siphonophrentis* and *Heterophrentis*, cemented by the gray sandy shale which forms strata above and below the coral bed. The top and bottom contacts are very sharp, only a slight faunal mixing being seen in the sandy shales above the bed. This coral bed was not found at Delphi Falls, a mile east, and the lateral relationships and extent of the bed are not known.

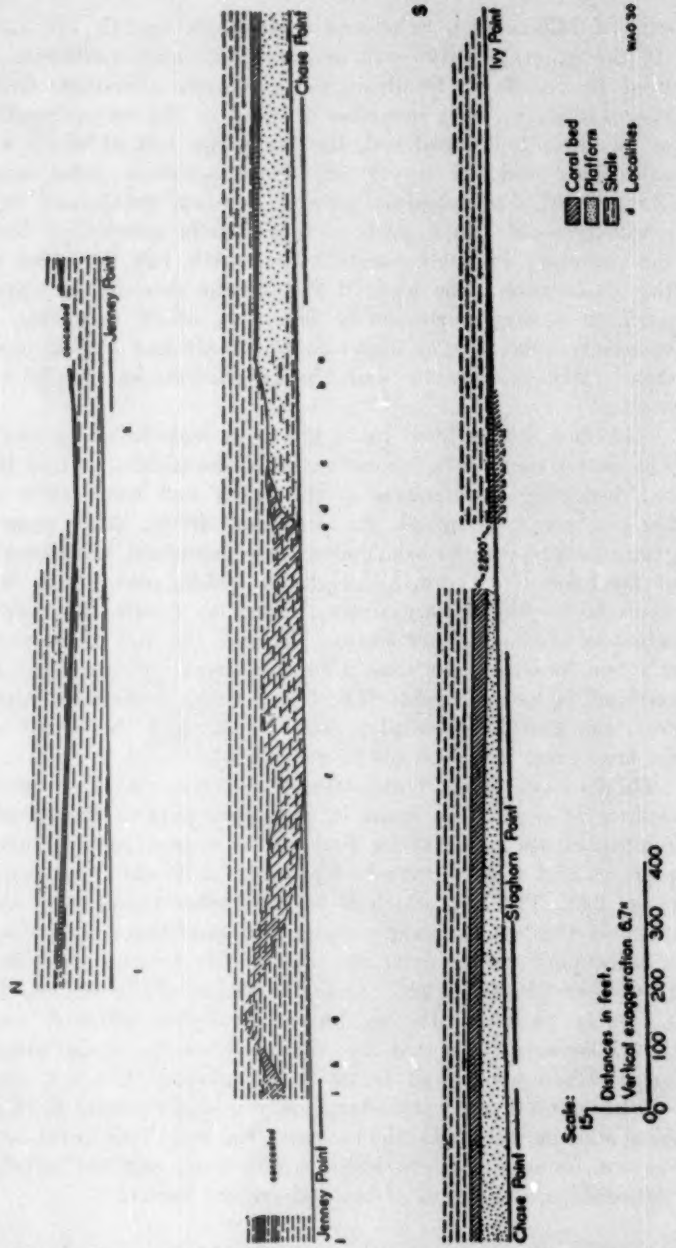


Fig. 4. Lower coral bed relations on the east side of Skaneateles Lake (locality 2).

The Delphi coral bed is much like the Ludlowville beds except for its small size and lack of a platform. The absence of fossils other than the rugose corals and the sharp contacts with the shale show that sedimentary and environmental conditions were similar to those of the larger beds.

Centerfield Coral Zone, Pennsylvania.—The coral bed at the base of the Ludlowville formation in eastern Pennsylvania was designated the Centerfield coral zone by Willard (1939, p. 178). According to him (1936, p. 32) the bed extends for 150 miles along the Hamilton outcrop belt in eastern Pennsylvania, having a thickness of 20 feet in the east, but thinning westward to about 3 feet in the Susquehanna Valley. The best exposure of the bed is in a road cut 3 miles north of Stroudsburg, Pennsylvania, where the thickness is about 13 feet.

The bed is quite different from the Ludlowville coral beds previously discussed. The fauna is not composed almost exclusively of rugose corals. Bryozoa, brachipods, pelecypods, trilobites, crinoid remains and tabulate corals are important constituents. In addition the rugose species and genera are somewhat different. The upper and lower limits of the bed are not sharply defined, a 2 or 3-foot transition zone being seen at the top and bottom. Willard correlated this zone with the Centerfield limestone of New York because of its fauna and apparent stratigraphic position. The New York Centerfield is noted for the coral elements of its fauna, but only locally is it reported to approach a coral bed in composition and structure. Apparently conditions for coral growth were somewhat less than optimum over most of the Centerfield sea. Locally in the Stroudsburg area, however, conditions were adequate for the development of a dominantly coral biocoenose.

Coral Beds, Ludlowville and Moscow of Western New York.—In the Hamilton group of western New York and Ontario there are many thin, localized, and more or less well defined coral beds. Most of these beds are found at or near the Centerfield or Tichenor (Encrinal) horizons, indicating patchy, temporary conditions favorable to coral growth and expansion.

Payne (1938, p. 53) points out the numerous corals to be found in the Centerfield member in Jaycox Run, 6 miles south

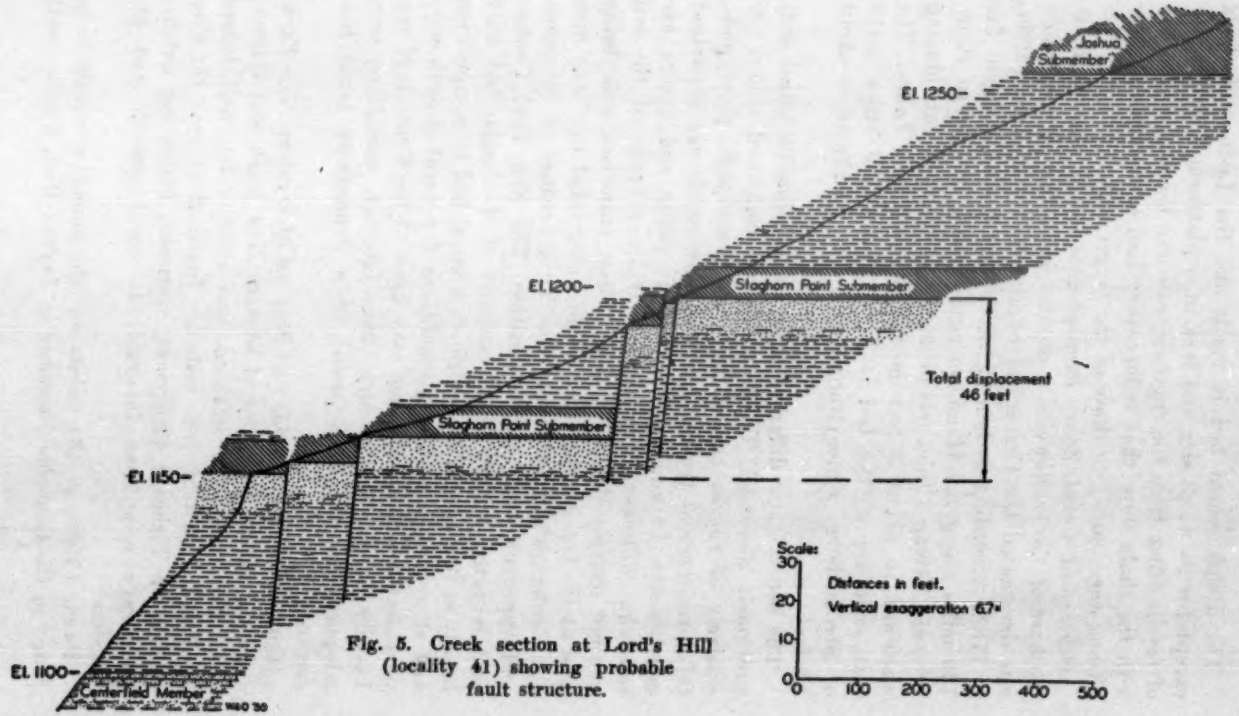


Fig. 5. Creek section at Lord's Hill (locality 41) showing probable fault structure.

of Avon, Livingston county. He says: "The sea bottom of Centerfield time like that of Onondaga time, must have been particularly ideal for the existence of corals, especially the individual cup corals, many types of which may be found." Farther to the west in the same county, "In the stream bed of a ravine just east of Rork a low dome-shaped reef structure packed with corals may be seen in the Centerfield." (*ibid.*). But according to J. W. Wells (personal communication), "It is hardly dome-shaped, rather lenticular, up to two feet thick, thinning east and west; there is a notable lack of *Siphonophrentis*, and other genera are represented by small individuals."

The Tichenor member in the York area is likewise described as virtually a coral bed. Hall (1843, p. 189) mentions a locality a mile west of York where the shale immediately below the Encrinal (Tichenor) limestone "is completely charged with Cyathophylli of different species, *Favosites* and other corals with some trilobites and shells." Further he states (p. 195) "some of the more abundant corals are identical" with these of the Onondaga.

Schuchert and Dunbar (1941, p. 204) refer to "local recurrences of coral reefs (as at East Bethany), made by species descended with little change from the Onondaga types that had persisted locally beyond the range of the early Hamilton black muds and now reestablished themselves where the waters were not too muddy." The occurrences west of East Bethany, Genesee County, are further discussed by Slocum (1906, p. 258) who mentions local coral concentrations in the shales just below the Encrinal [actually Centerfield, not Encrinal (Tichenor)]. Brachiopods and other fossils are commonly associated with the corals.

Grabau (1898, p. 29) discusses a "coral layer . . . eighteen or twenty inches above the Encrinal limestone." The layer is found in the Eighteen Mile Creek section and along Lake Erie, south of the creek mouth.

> "It is about three inches thick, and in most places consists entirely of an accumulation of cyathophylloid or cup corals. There are mostly of the genera *Heliophyllum* (*H. halli* E. and H.), *Cystiphyllum* and *Zaphrentis*, and nearly all lie prostrate...They show, however, no signs of wear, the delicate bryozoans and small corals which encrust many of them, showing that little if any disturbance has occurred...They there-

> fore indicate a flourishing coral reef or forest, which was suddenly overwhelmed, probably by the influx of muddy waters..."

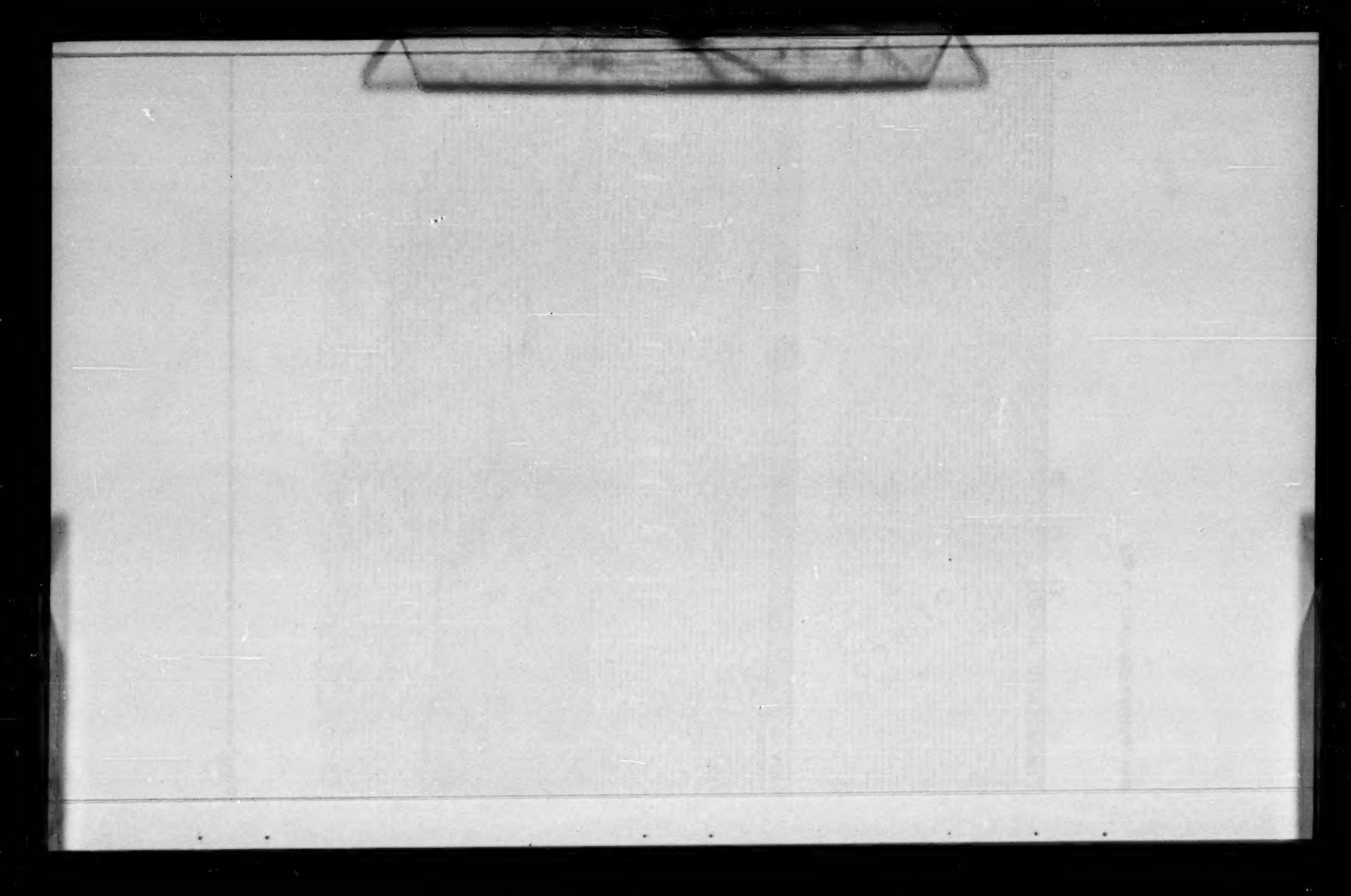
Curiously enough, the average size of the individuals in this lower Moscow (Windom member) coral zone is much larger than at most of the outcrops of the Centerfield and Tichenor coral zones in the West Central part of the state.

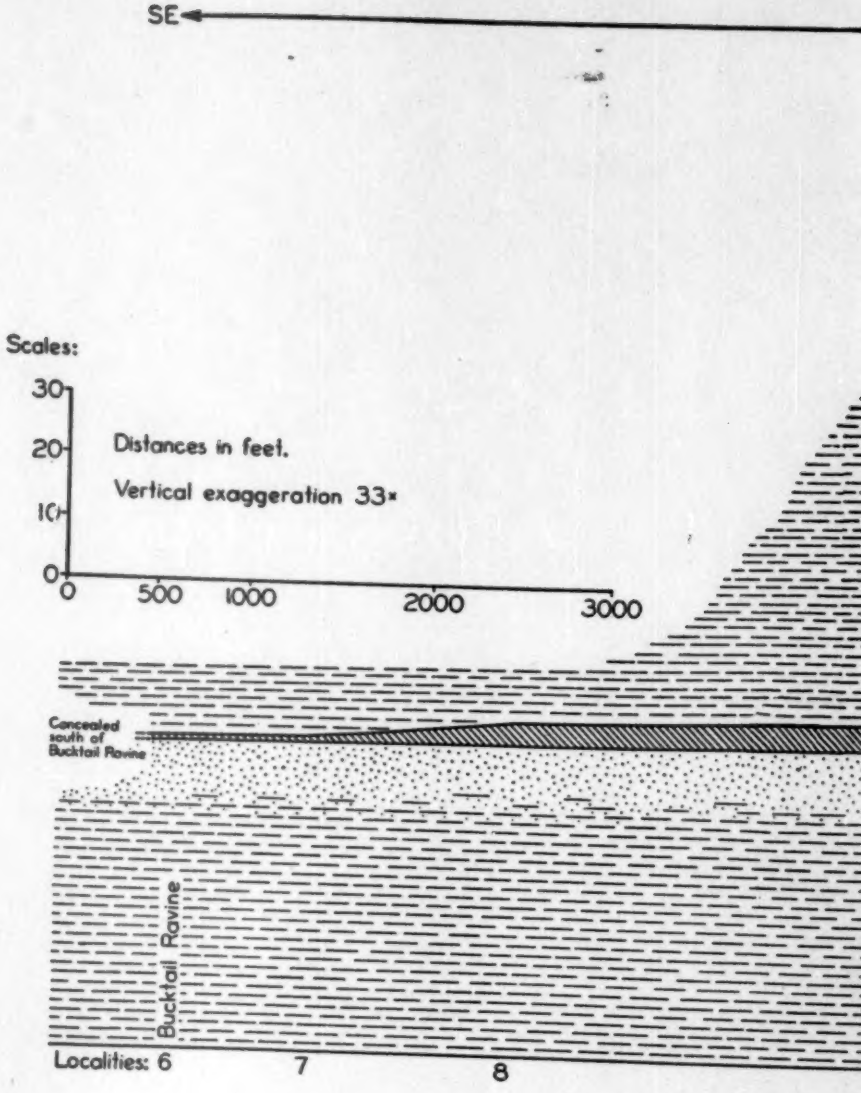
Grabau also noted that the small rugose coral *Streptolasma* [*Stereolasma*], common in the shales above and below the "coral layer," is not present in the "coral layer" itself, a situation similar to that found in the Ludlowville coral beds in central New York. Brachipods are common in the bed where the corals are not concentrated but seem to be almost absent in the well developed part of the coral bed (Grabau, 1899, p. 320).

A similar coral bed is described by Shimer and Grabau (1902, p. 152) from the vicinity of Thedford, Ontario. They state that it has the same position as the Eighteen Mile Creek bed, but more recent work by Cooper and Warthin (1942, p. 878) indicates that it is Centerfield, not Tichenor, in age. The bed differs from Grabau's "coral layer" in having a brachipod fauna equal in importance to the coral fauna. Differences are also noted within the coral faunas, although *Heliophyllum halli* and *Cystiphyllum vesiculosum* [*americanum*] are very important in both beds.

Summary.—These beds all have many features in common with the two great Ludlowville coral beds. They are thin, bedded structures of considerable horizontal extent. Further, they all have many coral genera and species in common which are closely related to, or derived from, the Onondaga coral fauna. Notably lacking, however, in the Ludlowville beds is the occurrence of the delicately ramose *Striatopora* and *Trachypora*, and hemispherical and pyriform forms of *Favosites* which are common in the other beds where the coral populations are not so concentrated.

With the exception of the Delphi coral bed and Cooper's *Meristella*-Coral zone, the beds described in this section are at either the Centerfield or Tichenor horizons. These two limestone bands are both of great lateral extent, and both indicative of rather calm, clear water environments where all forms of marine life, corals included, flourished. The coral




SE
Scales:
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20
10
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Distances in feet.
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Concealed south of Bucktail Ravine
Bucktail Ravine
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7
8

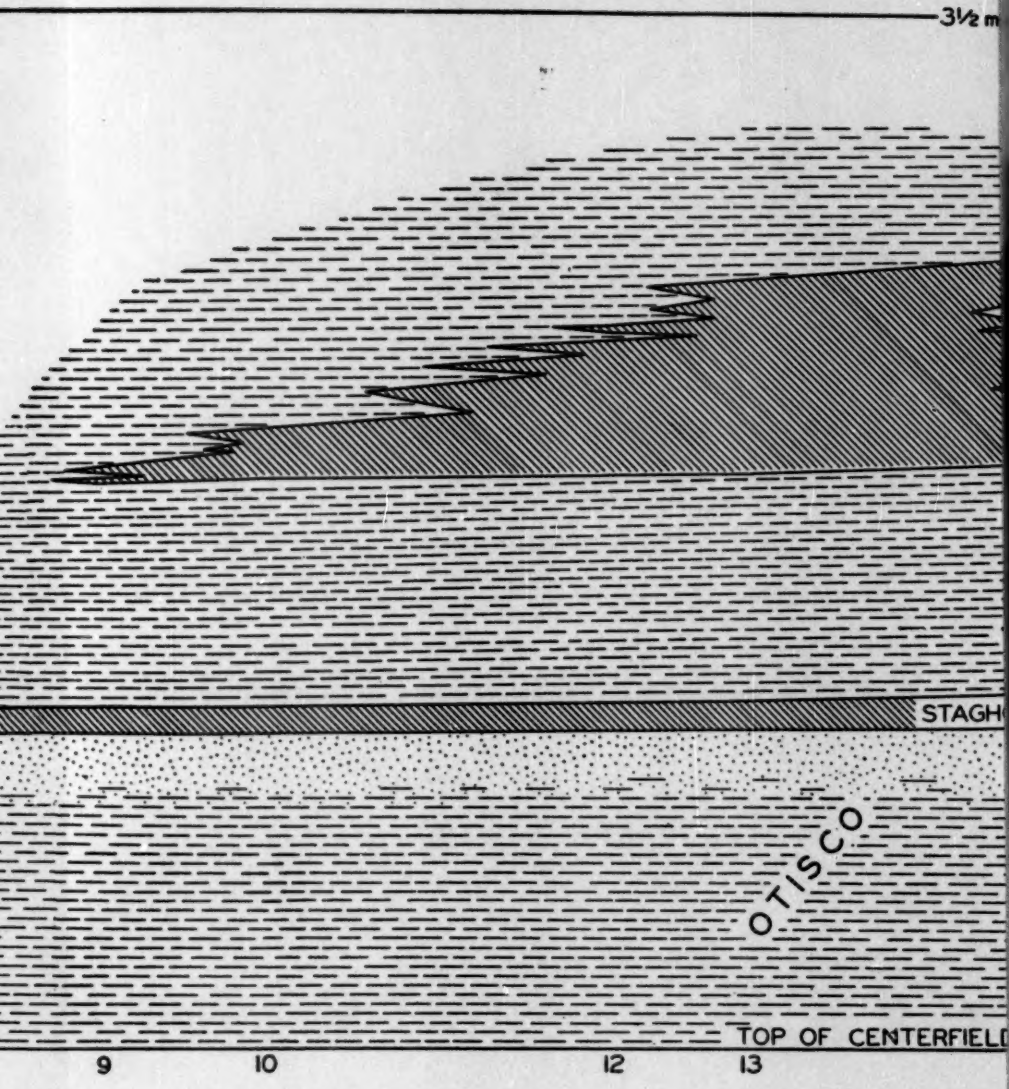
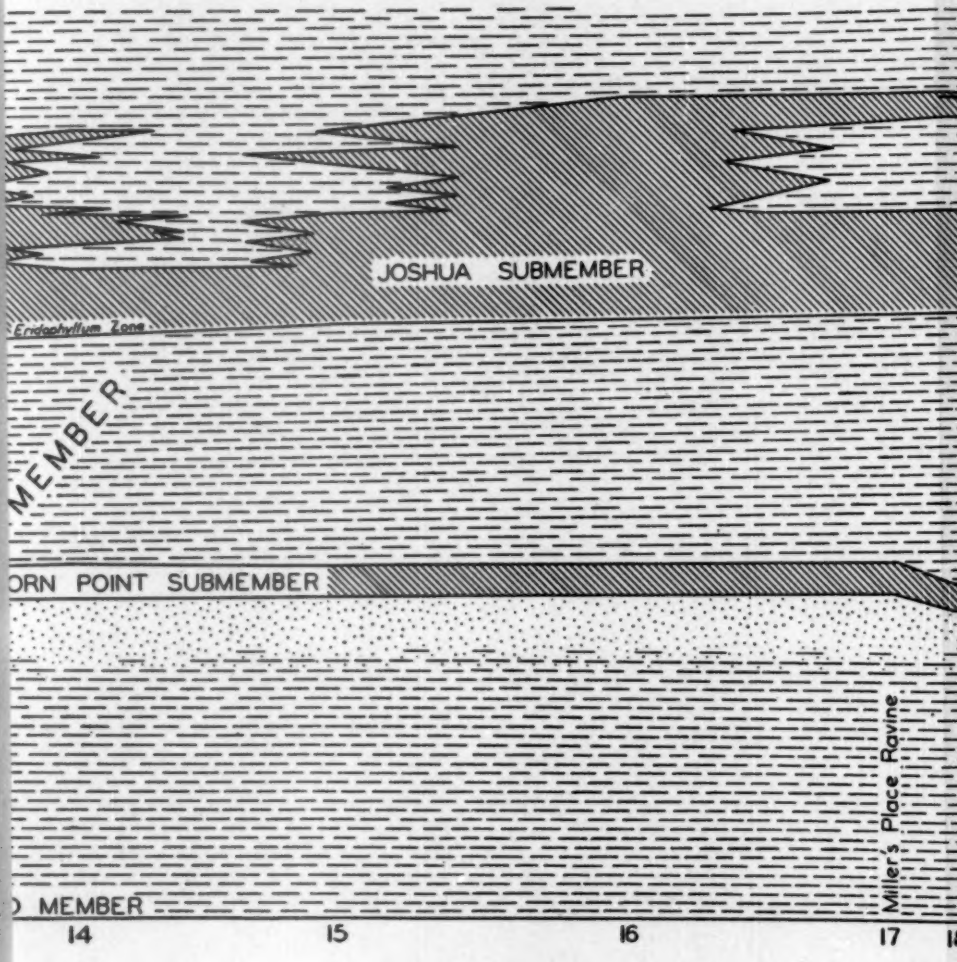
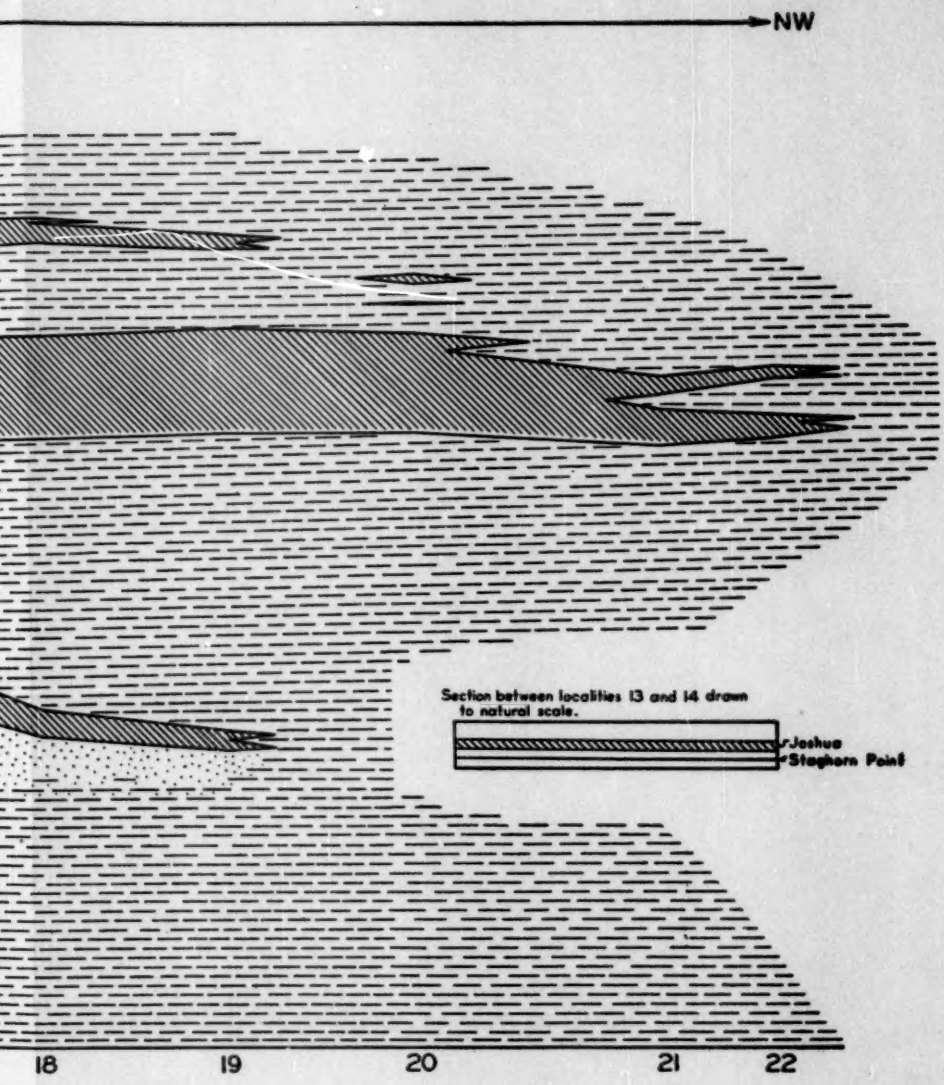


Fig. 6. Coral bed relations, west



side of Otisco Valley.


NW
Section between localities 13 and 14 drawn to natural scale.
Joshua
Staghorn Point
18
19
20
21
22

W.A.O. '50

beds at these horizons seem to represent localized conditions here and there so favorable to coral growth that other organisms were more or less excluded, but nowhere so much so as in the Ludlowville coral beds in Onondaga County. They differ markedly from the Ludlowville coral beds in their lateral relations. Centerfield and Tichenor coral zones or beds are characterized by a complete lateral faunal gradation into the normal "limestone," with isolated individuals to be found at all exposures of the limestones. In contrast the Ludlowville beds are isolated structures whose horizon is not recognizable away from the coral beds proper either faunally or lithologically.

SUMMARY AND CONCLUSIONS

The coral biostromes of the Staghorn Point and Joshua submembers, represent recurrences of relatively clear, warm, shallow water conditions, but less than the reef optimum of Onondaga time. At these times of biostrome development, corals were able to multiply rapidly and colonize whole areas to the nearly complete exclusion of other organisms. Exceptionally favorable conditions for solitary rugose corals were reached during Staghorn Point time and repeated in Joshua time, and coral plantations spread over large areas.

Ripple marks indicate that the sandstone platform below the Staghorn Point submember was deposited by southeasterly currents which, probably as a result of shoaling over the area concerned, bypassed the muds and left a residue of fine sand. The cause of the shoaling as well as the relationship of the shallow area to currents is unknown but the ripple marks indicate that the current was roughly at right angles to the long dimension of the platform. The distribution of the platform determined the lateral extent of rich coral colonization.

With the sandy platform on which to establish a foothold, the corals were able rapidly to expand their holdings over a broad area. Succeeding generations used the skeletons of their predecessors as a substratum. Occasionally greater influxes of muds than could be bypassed overwhelmed local areas, overturning and abrading the corals. This is indicated by the coarse, irregular bedding of the submember and by the worn condition of many of the corals, most of which are

not in their living positions. Following such events the corals would quickly reoccupy the area. Fanning or interfingering zones of corals at the extremities of the bed indicate temporary extensions beyond the limits of the platform.

The history of the Joshua submember is very similar to that of the Staghorn Point. However, studies of the tabulate corals by Mrs. Mary Ross of Cornell University show that Staghorn Point specimens are flat and expanded or branching forms while the Joshua tabulates are thick, massive forms, many with knobby surfaces, with none of the delicate, branching types. Studies of recent corals (Vaughan and Wells, 1943, p. 60) have shown that branching forms are characteristic of quiet, shallow water and that encrusting or massive forms are indicative of rough water. While these criteria cannot positively be applied to the extinct tabulates, it is likely that the reactions to rough water would be similar in unrelated groups of similar form. The tabulates, then, suggest quiet, shallow water conditions for the Staghorn Point coral bed, as postulated above, and somewhat rougher water in Joshua times.

It has been pointed out that there is no sandy platform beneath the Joshua submember. Instead, at almost every exposure of the upper coral bed there is a basal *Eridophyllum* zone. Apparently this colonial rugose coral acted as a colonizer, the solitary corals only being able to establish themselves on the "platform" formed by *Eridophyllum* skeletons. The orientation of this "platform" (fig. 2) is more easily explainable. Modern coral reefs and banks are ordinarily positioned at right angles to the direction of food carrying, oxygenated water movements. A southeasterly current would thus be indicated by the Joshua bed. This is not inconsistent with sedimentary evidence of general current direction in this part of the Appalachian geosyncline during Devonian time.

After the establishment of the platform, further development was much the same as that postulated for the Staghorn Point bed. The corals did not spread over so great an area, but successful colonization endured longer. Extensions beyond the "platform" met with the same lack of success, and the lateral relations of the two coral beds with the Otisco shale are much the same.

The beds were probably developed too far offshore to bear

any special relationship to the eastern shore line. Easterly the Otisco gray shales grade into sandy shales, sandstone, and finally continental deposits in a distance of some eighty miles.

The other coral beds cited from the Hamilton of New York occur in the same gray shale phase (*Tropidoleptus* fauna) as the Ludlowville beds. There is a progressive stratigraphic rise westward with this phase. The easternmost bed, Cooper's *Meristella*-Coral Zone (Berne Quadrangle), is found in the top of the Marcellus formation; in the Cazenovia Quadrangle, there is a thin coral bed in the Skaneateles formation; in the Tully and Skaneateles Quadrangles are the great coral beds of the Ludlowville formation; and there are weak coral beds in the Ludlowville and Moscow formations farther westward in the state. This regressive westward shift parallels the corresponding regressive shifts of the more westerly dark or black shale phase (*Leiorhynchus* fauna) and the more easterly sandy, pelecypod phase. This westward regression is presumably correlated with steadily rising land masses to the east.

Coral bed development is but one aspect of the overall phase-facies relations of the Hamilton group of deposits. This development reached its peak in the Staghorn Point and Joshua biostromes when "forests" of corals covered many tens of square miles, maintaining themselves for long periods of time, but ultimately being overwhelmed by the muds.

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CORNELL UNIVERSITY
ITHACA, NEW YORK

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MECHANICS OF ASH FORMATION

J. VERHOOGEN

ABSTRACT. Conditions which might lead to formation of ash are investigated, and it is found that they do not depend in any simple way on viscosity or gas content of the magma. The most important single factor appears to be the number of bubbles which form per unit volume and unit time. The problem is similar to that of nucleation of crystals; and it is argued that differences in behavior of erupting volcanoes may depend more on the kinetics of the processes involved than on original differences in composition, gas content, depth, etc.

1. It is generally accepted that formation of ash and, more generally, explosive behavior of magma, depend largely on viscosity and gas content: high viscosity and large gas content would be conducive to explosive phenomena, whereas lavas of low viscosity would "boil" more gently as they do in lava lakes of the Hawaiian type. The viscosity of a magma, in turn, increases strongly with increasing silica content. It is also generally assumed, without very good grounds, that silica-rich magmas are higher in water content; and although it is known that a high water content decreases the viscosity of a silicate melt, it has become customary to associate explosive phenomena with silica-rich magmas. While it is true that great explosions and formations of vast quantities of ash do occasionally accompany eruption of rhyolitic and dacitic magma (Krakatoa, Katmai), there are nevertheless many instances on record of explosive activity in basic magmas (Vesuvius, Tamboro, Coseguina), and basaltic tuffs and ash deposits are not rare (Sonder, 1937). It may therefore be of interest to evaluate quantitatively the relative importance of viscosity, gas content, and other relevant factors. Such is the purpose of the present paper.

We shall not enter here into a detailed discussion of the fundamental causes of explosive activity. Let it be assumed that for some reason,—rising of magma, opening of fissures, reheating, crystallization—the external pressure acting on the silicate-water melt has become less than the vapor pressure of this melt, that is, the pressure of the water vapor phase that would be in equilibrium with it. Let Π, the "oversaturation," be the vapor pressure minus the actual pressure; then, if Π is positive, a certain amount of water comes out of solution

in order to decrease the vapor pressure, and vesiculation begins.

The word "ash" will be used here to designate very small pyroclastic fragments of juvenile material, *i.e.*, the product of extreme fragmentation of fresh lava. Such extreme fragmentation of liquid material must be accompanied by a large volume expansion; and in this sense "ash formation" and "volcanic explosion" are taken to be almost synonymous. It is realized, however, that certain types of volcanic explosions do not produce juvenile ash; the finest fragments blown out in many cases may be produced by mechanical disintegration of older material. Such explosions do not necessarily involve rapid gas evolution from the melt; they may be caused by previous accumulation of a separate homogeneous gas phase. We shall be concerned here essentially with two-phase foam produced when gas evolution is still taking place.

2. Let us now consider what happens when vesiculation begins. If a few bubbles form and rise swiftly by buoyancy to the surface, the lava will "boil" as it does in lava lakes. If, on the contrary, a large number of bubbles expand more rapidly than they rise, a time may come when neighboring bubbles begin to coalesce. When such coalescence becomes general the lava will be fragmented into small shreds of liquid or glass between adjacent bubbles, and may lose is cohesion. If, in addition, the pressure in the bubbles is still large at this time, the fragments will be blown apart, producing an explosion the intensity of which will depend essentially on the magnitude of this residual pressure. If it is small, we might observe a mild motion of a slowly expanding dust cloud ("sand flow" type); if the pressure is large a violent outburst of Vulcanian or Plinian type might occur.

It would thus appear that a preliminary condition for ash formation is that the lava should lose its cohesion by coalescence of a large number of bubbles expanding radially faster than they can rise and escape at the surface. Hence one might suggest as a preliminary condition for ash formation that

$$u > v \tag{1}$$

where u is the velocity of expansion and v the upward velocity which will be given by Stokes' law

$$v = \frac{2g\rho r^2}{9\eta} \tag{2}$$

where r is the radius of a bubble, g the acceleration of gravity, ρ the density of the melt and η its viscosity.

3. To compute $u = \frac{dr}{dt}$, consider a single bubble expanding from an initial radius r_o. This initial radius cannot be taken to be o, because of the surface tension σ at the liquid-gas interface. The pressure inside the bubble due to this surface tension alone, would be $2\sigma/r_o$, and this cannot be greater than Π, otherwise no bubble would form. As σ may be of the order of several hundred dynes per cm^2, and as it is doubtful whether Π ever exceeds a few thousand bars, r_o cannot be less than about 10^{-6} cm. This means that a bubble will form and grow only when, by random fluctuation, a few hundred molecules of water have clustered together in the melt. Thus to avoid surface energy considerations, let us choose as time of origin the time $t = o$ at which the bubble has reached a size r_o not less than 10^{-5} cm. Let P_o be the pressure in the bubble at this stage, and P the pressure when the bubble has expanded to a radius r.

The rate of expansion may then be computed along the lines suggested by Rayleigh, 1917. (See also Lamb, 1932, p. 122.) If u is the radial velocity of the boundary of a bubble of radius r, the velocity U in the liquid at a distance R from the center of the bubble is, in an incompressible fluid, such that

$$U = u\frac{r^2}{R^2}$$

The kinetic energy E of the liquid surrounding the bubble is

$$E = \frac{1}{2}\rho\int_r^\infty U^2 4\pi R^2 dR = 2\pi\rho u^2 r^3 \qquad (3)$$

whereas the work W done by the expansion of the gas is

$$W = \int_{V_o}^{V} PdV$$

If the expansion occurs adiabatically

$$P_o V_o^\gamma = PV^\gamma \qquad (4)$$

γ being the ratio of specific heats. Since $V_o = \frac{4}{3}\pi r_o^3$, $V = \frac{4}{3}\pi r^3$,

we have

$$W = \frac{4}{3}\pi \frac{1}{\gamma - 1} P_o r_o^3 \left[1 - \left(\frac{r_o}{r} \right)^{3(\gamma-1)} \right] \qquad (5)$$

Equating (3) and (5) and setting for simplification $\gamma = 1.33$ (actual value for water $\gamma = 1.29$) we have

$$u^2 = \frac{2P_o}{\rho} \frac{r_o^3}{r^3} \left(1 - \frac{r_o}{r} \right) \qquad (6)$$

which shows that u decreases with increasing r. The upward velocity v, on the contrary, increases with increasing r. Thus small bubbles may expand faster than they rise, whereas large bubbles would rise faster than they expand. Condition (1) becomes

$$\frac{2P_o r_o^3}{\rho r^3} \left(1 - \frac{r_o}{r} \right) > \frac{4g^2\rho^2 r^4}{81\,\eta^2} \qquad (7)$$

We note from (4) that if there is no introduction of new material into the bubble as it expands, r cannot increase indefinitely, since P can never be less than the pressure acting on the melt, which would be at least 1 bar. Hence, even if P_o is as high as 10^4 bars, r should always be less than $10r_o$. Hence (7) becomes, for $r_o = 10^{-3}$ cm, $\rho = 3$ gm/cm^3

$$P_o > 7.4 \times 10^{-7}/\eta^2$$

and since η would not be less than 10^5 or 10^6 c.g.s. units, condition (7) will always be satisfied. Thus the bubbles expand very rapidly *in situ* to their maximum size $r = 10^{-4}$ cm., and if the number n of bubbles per cubic centimeter is such that $n^{-1/3} \cong r$, the bubbles will coalesce and the lava will be reduced in a very short time (as compared with the time it would take the bubble to reach the surface) to a dust (particles about 10^{-4} cm.) with a small internal pressure. The condition is, however, that

$$n \cong r^{-3}$$

or

$$n \cong 10^{12}$$

which is very large. If $n < 10^{12}$, as would probably be the case, the lava vesiculates, but does not lose its cohesion.

4. It may be useful to investigate a further effect of viscosity. Theoretically, when a single bubble expands radially, the motion of the (incompressible) fluid around it is also radial and irrotational; there is no dissipation of heat by viscous friction. But if a large number of bubbles grow simultaneously towards each other, the radial velocity of the fluid

in between will be checked at some points and increased at others, and some dissipation of energy may be expected. This heat, however, would merely raise the temperature of the fluid and presumably also that of the gas in the bubbles, offsetting somewhat the cooling due to adiabatic expansion. Remembering that in the case of a lava containing only a few per cent of water, the mass of the gas bubbles will be small compared with that of the liquid, we might consider an extreme case in which the bubbles expand at constant temperature. We have then

$$P_o V_o = PV$$

and, for a perfect gas

$$W = 3\,RT_o \ln (r/r_o)$$

R being the gas constant and T_o the temperature of the lava. We have then

$$u^2 = \frac{2\,P_o}{\rho}\,\frac{r_o^3}{r^3}\,\ln\,(r/r_o) \qquad (8)$$

and numerical substitutions indicate that the conclusion of the preceding paragraph is not greatly altered.

5. It should be noticed that in both cases considered above (adiabatic and isothermal) there is a maximum radius r which cannot be exceeded. This is due to the assumption that no water enters the bubble as it expands. Now it is unlikely that the whole amount of water which has to come out of the melt to reduce the oversaturation to zero should come out at once; more probably bubbles would continue to form for some time and more water would diffuse into them as they grow. Let m be the number of moles of water in a bubble of volume V. We have then, at sufficiently high temperature, approximately

$$P = mRT/V$$

If the expansion occurs isothermally, as suggested above, the rate of change of pressure with time is

$$\frac{dP}{dt} = -\frac{m}{V^2}\,RT_o\,\frac{dV}{dt} + \frac{RT_o}{V}\,\frac{dm}{dt}$$

Now $V = \frac{4}{3}\pi r^3$, $dV/dt = 4\pi r^2 u$. Assuming further that the amount of water entering the bubble per unit is proportional to its surface: $dm = K4\pi r^2$ we have:

$$u = \frac{1}{P}\left[RT_oK - \frac{r}{3}\,\frac{dP}{dt}\right] \qquad (9)$$

6. It has frequently been observed that when a volcanic explosion occurs, fragments are blown out with an initial velocity which suggests that the pressure, at the time of fragmentation, is still large (a few hundred atmospheres) and comparable to Π. Thus, to a first approximation, we might take $P = P_o = \Pi$ and $dP/dt = 0$. The density ρ_o of the water vapor in the bubbles then remains constant during the expansion and we have

$$u = K\frac{RT_o}{P_o} = K\mu/\rho_o \qquad (10)$$

where μ is the molecular weight of water (18).

Let r_o be the radius of the bubbles at the time of fragmentation, i.e., when the bubbles begin to coalesce; hence $r_o \cong n^{-1/3}$. The time Θ required for a bubble to expand from r_o to r_e at the constant rate (10) is

$$\Theta = \frac{r_e - r_o}{u} = \frac{r_e - r_o}{\mu K}\rho_o$$

the average radius r during this interval of time is $r = r_o + \frac{1}{2}\frac{uK}{\rho_o}\Theta$ and the distance l this average bubble would rise is, by Stokes's law (2)

$$l = \frac{2g\rho}{9\eta}\left(r_o + \frac{\mu K\Theta}{2\rho_o}\right)^2\Theta$$

If l is less than h, the average distance a bubble has to travel to reach the surface [h, for instance, would be half the thickness of a recently erupted lava flow] fragmentation and formation of ash will occur. Thus the condition for ash formation becomes

$$\frac{2g\rho}{9\eta}\left[r_o + \frac{\mu K\Theta}{2\rho_o}\right]^2\Theta < h$$

or

$$\frac{g\rho\rho_o}{18\eta\mu K}\left(r_e + r_o\right)^2\left(r_e - r_o\right) < h \qquad (11)$$

Let us now assume $r_e \gg r_o$, i.e., $n \ll 10^{15}$. The density ρ_o of the water vapor must of course be such that the total amount of water in the bubbles, at their maximum size, viz. $n\frac{4}{3}\pi r_e^3\rho_o$, cannot exceed the initial amount of water in the melt ρx, where

x is the percentage (by weight) of water. Hence, since $r_e \cong n^{-1/3}$

$$\rho_o < \frac{3\rho x}{4\pi}$$

Hence (11) becomes

$$\frac{g\rho^2 x}{24\pi\eta\mu \mathrm{Kn}} < h \qquad (12)$$

7. Let us now evaluate K, the number of moles of water crossing a unit surface at the boundary of a bubble per unit time. If D is the diffusion coefficient of water in the melt, and $-\,dc/dr$ its concentration gradient

$$K = D\frac{dc}{dr} \qquad (13)$$

to the approximation to which the chemical potential is proportional to the concentration. Now if c_o is the concentration (in moles per cm.^{3}) half way between two bubbles, the centers of which are $n^{-1/3}$ cm. apart, the average gradient is $2c_o/n^{-1/3}$. We have $c_o = \rho x/\mu$. For D we take the classical Stokes-Einstein relation

$$D = \frac{RT_o}{6\pi\eta r_m N_o} \qquad (14)$$

where N_o is Avogadro's number, η is the viscosity of the medium in which diffusion occurs, and r_m is the radius of a diffusing particle. Equation (12) becomes

$$\frac{g\rho r_m N_o}{8RT_o n^{4/3}} < h \qquad (15)$$

Take $N_o = 6.02 \times 10^{23}$, $r_m = 3\times10^{-8}$ cm., $g = 980$ cm. sec^{-2}., $\rho = 3$gm. cm^{-3}., $R = 8.31\times10^7$ erg/deg. Then the condition for ash formation becomes

$$n^{4/3} > \frac{8.2\times10^7}{T_o h} \qquad (16)$$

which appears to be independent of the characteristics of the magma itself (viscosity, water content, etc.). The number of bubbles per unit volume required to form ash decreases with increasing temperature and increasing depth at which vesiculation takes place. If we set, for instance, $T_o = 1000°$C $h = 10^4$ cm., we have approximately

$$n > 700$$

Fragmentation will then occur if there are more than a few hundred bubbles per cm.^{3}.

8. The above analysis, although grossly oversimplified, brings out the fact that the behavior of the magma will depend essentially on the number of bubbles which form; it is therefore essentially a problem in kinetics of nucleation, similar to the problem of predicting the texture of an igneous rock. Rather surprisingly, viscosity does not appear explicitly in equation (16). The reason for this is that viscosity has two opposing effects which cancel mutually. On one hand, a high viscosity prevents the upward motion of bubbles, favors their development *in situ* and enhances therefore the probability of coalescence and fragmentation of the lava. On the other hand, it has been shown in sections 3 and 4 that a bubble cannot grow very much unless it is fed as it grows; and equation (14) and (15) show that high viscosity retards diffusion from the melt into the bubbles, thus preventing them from growing.

It should be noted, however, that n itself must depend on viscosity, which reappears therefore implicitly in equation (16). It is unlikely indeed that all bubbles should form at the same instant; more probably, new bubbles would form as time goes on, and as they expand gradually, there would be at any time a certain frequency distribution of bubbles with respect to size. Now larger bubbles rise faster than smaller ones, the difference in upward velocity depending on viscosity. If viscosity is low, the larger bubbles will overtake on their way up the smaller ones, which are travelling more slowly and will be swallowed up. Larger bubbles would tend to become still larger, while the population of smaller ones would be depleted. Possibly this is the mechanism responsible for the occasional large bubbles which come to burst at the surface of a fluid lava lake.

We should therefore write for n an expression of the type

$$n_t = n_o + \int_o^t \nu' \, dt - \int_o^t \nu'' \, dt \qquad (17)$$

where n_o is the number of bubbles at time $t = o$, and ν' and ν'' are respectively the rates at which new bubbles form and are swallowed up. Clearly, if ν'' is large enough, n might never reach the critical value (16). It will be remembered that the time $t = o$ was chosen in section 3 as the time at which the bubbles have already reached a size sufficient to make surface tension effects negligible; it might be appropriate to return now to

the more natural time origin at which the oversaturation Π begins to develop, making thus $n_o = 0$.

9. The value of ν'' could probably be computed without too much trouble, given a certain size distribution of bubbles at a certain time. This size distribution, however, would depend on time, rate of growth and on ν', the rate at which new bubbles form; and the problem of computing ν' is indeed a formidable one. The best that can be done here is to outline a few factors which are likely to affect ν'.

In the first place, nucleation rates are known to be proportional to exp ($\Delta G/RT$) where ΔG is the (Gibbs) free energy change involved in nucleation. Two factors contribute to ΔG: the energy required to form a new gas-liquid interface, which depends on surface tension, and the difference in chemical potential of water in the melt and in the bubble, which depends on the oversaturation. It should be noted that Π does not depend directly on water content; Π is the difference between the pressure acting on the melt and the vapor pressure, which in turn depends on water content, temperature, and composition of the melt. A magma containing little water, but which is strongly oversaturated (due, for instance, to a drastic reduction of the external pressure), might vesiculate faster than a water-rich magma which is only moderately removed from its equilibrium state. Formation of ash need not, in the writer's opinion, be confined to water-rich melts; the magnitude of the oversaturation Π seems to be a more relevant factor. It is perhaps worth mentioning here that Π is not necessarily positive when the pressure of the melt is reduced, or when the magma rises in a volcanic conduit; the contrary may be true if osmotic conditions prevail (Verhoogen 1949, p. 125).

Another important factor which may affect ν' is the degree of crystallization of the magma at the time when oversaturation develops, for it is known that heterogeneous nucleation (that is, nucleation at an interface between, say, liquid and suspended crystals) is considerably easier than nucleation in an homogeneous phase (Turnbull, 1950). Bubbles would develop preferentially around small crystals. At the same time, abundance of suspended crystals would probably increase the overall viscosity of the magma, decreasing thereby ν''. High crystallinity would thus favor ash formation; and this may explain why, as was pointed out to the writer by Howel

Williams, catastrophic explosions of historic times in basic magmas (e.g., Tamboro) have usually produced crystal-rich ejecta.

Finally, one would expect that v' would depend markedly on the rate at which the oversaturation develops, just as the texture of an igneous rock depends on the rate of undercooling, v' would probably increase with increasing $d\Pi/dt$, although the behavior would be different when Π results from changes in pressure or from increase in temperature. Due to the endothermal character of gas evolution (neglecting hypothetical exothermic reactions) and to the marked effect of temperature on viscosity, there might exist, as in the case of crystallization, an optimum value of $d\Pi/dt$ for which v' would be maximum. One might therefore expect to observe differences in behavior when the external pressure decreases slowly, as when magma ascends slowly in an open conduit, or when the external pressure is reduced suddenly by opening of fissures, or when the oversaturation results from reheating. In some cases it might be necessary also to consider the rate of change of the pressure of hydrodynamic origin. Also, in all these cases, the actual beginning of nucleation might lag behind the oversaturation, for "incubation" effects may exist as in crystallization or phase transformation. The present writer would suggest, for instance, that a "nuée ardente" is an example of such delayed action in which the evolution of gas is slow, and starts only some time after the oversaturation has developed either as a result of reheating or of a preliminary Vulcanian explosion of a separate gas phase. Similarly, one may suggest that the gradual increase in explosive intensity which leads to a climax of Krakatoan type is not necessarily due to ascent of magma progressively richer in gas: it may be related purely to the kinetics of nucleation and gas evolution.

10. Summing up, ash formation is believed to depend essentially on the kinetics of gas evolution, the crucial factor being the number of bubbles per unit volume which may be present at a certain time. Initial water content of the magma, degree of oversaturation, rate at which oversaturation develops, cause of oversaturation, viscosity, surface tension, temperature, depth, nature and amount of suspended crystals, are among the factors which determine the rate and mode of

gas evolution, without much indication of any of these being more important than the others; for instance an expression was derived in section 7 in which viscosity and water content do not even appear explicitly. One may be tempted to generalize and propose that many other volcanic manifestations besides formation of ash depend more on kinetic than on purely thermodynamic considerations. An erupting volcano is certainly not in equilibrium; volcanic phenomena do not correspond to transition from an initial to a final state through intermediate equilibrium states. Hydrogen and oxygen may combine explosively to form water in presence of a spark, or they may coexist in metastable equilibrium, or they may combine slowly in the presence of appropriate catalysts; yet the thermodynamic characteristics are the same in all three cases. Similarly, differences in volcanic behavior, as between Pelean and Vulcanian explosions, formation of aa and pahoehoe, quiet outflow and explosion of pumice, are not necessarily related to profound differences in initial water content, or temperature, or depth; and it may be futile to attempt to classify volcanic phenomena in terms of one, or even two variables only. It is more probable that at least half a dozen variables should be required for an adequate analysis, and that such differences as are observed depend on a combination of a large number of apparently insignificent, or at least not very obvious, factors.

In conclusion, the writer wishes to thank his colleagues Howel Williams, W. H. Mathews and G. H. Curtis for stimulating discussions on this subject.

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Department of Geological Sciences
University of California
Berkeley 4, California

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THE GREAT SMOKY FAULT*

ROBERT B. NEUMAN

ABSTRACT. Precambrian rocks of the Ocoee series and Cambrian rocks of the Chilhowee group are faulted against Middle Ordovician shales (Athens, Tellico and Sevier of older reports) along the Great Smoky fault in eastern Tennessee. The movement plane of this fault appears to have been governed by the lubricating properties of the shales of the autochthone, whereas the sole of the allochthone does not follow a stratigraphic horizon. The Guess Creek fault, defined herein, has less throw, but along part of its extent Middle Ordovician shales are thrust over rocks of Mississippian age.

INTRODUCTION

NEW observations have been made on the Great Smoky fault and the rocks that adjoin it. This report presents information obtained by the writer and others who are members of a party that is studying the stratigraphy and structure of the Great Smoky Mountains National Park and vicinity (fig. 1) for the U. S. Geological Survey. Although this project was initiated in the autumn of 1946, the work is now only about half completed. This is, therefore, a progress report, for conclusions may be modified as further information is obtained during the later phases of the project.

The writer has been interested primarily in the Ordovician rocks that adjoin the Great Smoky fault, but during the course of his work on them he has had occasion to map the fault along many miles of its trace. In addition, he has benefited from information obtained on the fault and adjoining geology by other members of the party, in particular that of Herman W. Ferguson of the Tennessee Division of Geology in the Walden Creek and Wear Cove quadrangles, and P. B. King in the Richardson Cove, Pigeon Forge, and Gatlinburg quadrangles. Maps of smaller areas in the Kinzel Springs quadrangle by G. D. Swingle (1949) and C. A. Tucker have also been consulted.

P. B. King aided the writer in the preparation of the text and illustrations of this paper, and offered many suggestions and criticisms.

PREVIOUS WORK

The first systematic work in the Smoky Mountains area

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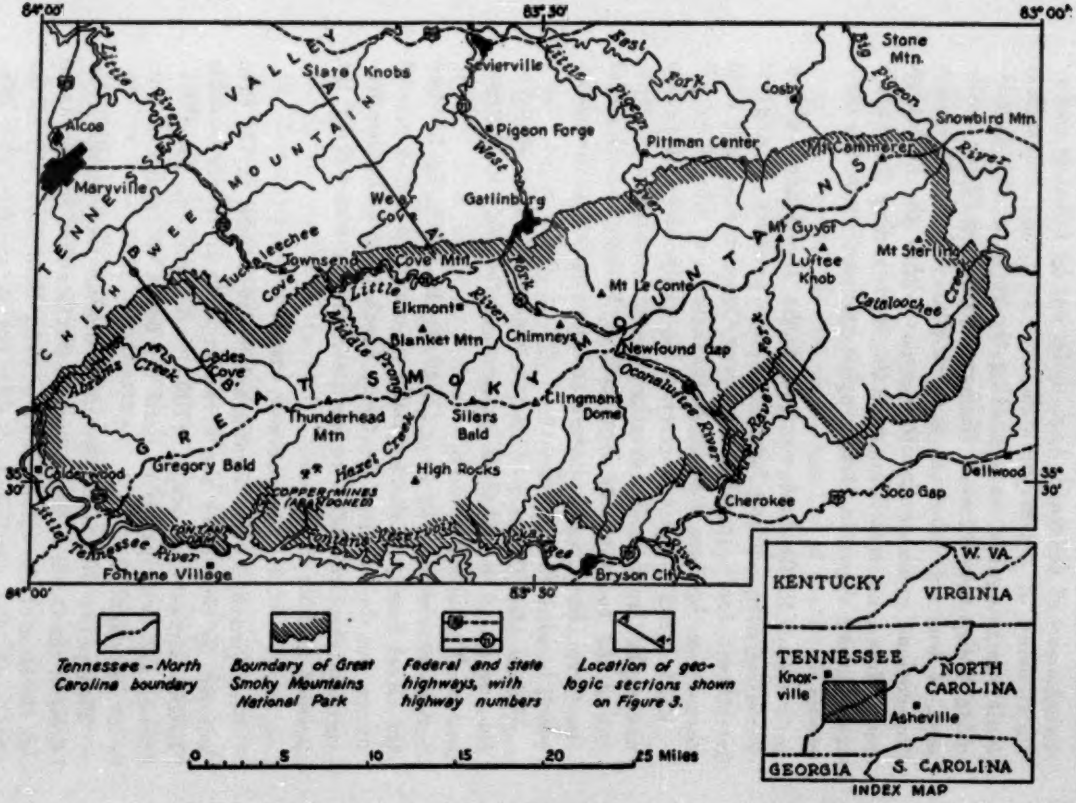

Fig. 1. Index map of Great Smoky Mountains area (from King, 1950b).

was by Arthur Keith, and the results were published in the Knoxville folio (Keith, 1895. He accurately differentiated many of the major rock units, but he failed to understand many of the major structural relations. Although a fault was recognized as separating the rocks of the Appalachian Valley from those of Chilhowee Mountain to the southeast, it was not shown as a continuous feature. Moreover, the curious coves or limestone areas within the mountains were shown as anticlines, and the surrounding "mountain rocks" were shown in stratigraphic sequence upon the limestones.

Gordon (1920) first recognized the significance of the limestone coves, noting here ". . . the presence of a great overthrust fault whereby the lower Ocoee rocks have been thrust over the Knox dolomite to the distance of 8 or 10 miles."

Keith (1927) later corrected his early views. He then named the Great Smoky overthrust and described it as separating the rocks of the Appalachian Valley from those of the Great Smoky Mountains, and as encircling the coves, which he identified as windows.

Wilson (1935) reported on two weeks spent in a study of the coves, and described an exposure of the fault at the east end of Tuckaleechee Cove.

Structure sections by King (1949, fig. 2; 1950b, fig. 3) show the Great Smoky fault essentially as conceived in the present paper, but do not show the Guess Creek fault and other features in the Ordovician rocks that were worked out by the present author.

PRESENT WORK

Stratigraphy.—The stratigraphic names used in the area covered by this paper are shown in table 1. Where possible Keith's names and usages (1895) are retained, but thicknesses and descriptions of units are based on results of current investigations.

This paper does not attempt to discuss the complex relations of the Ocoee series. A sericite phyllite that is here placed at the base of the column may be older than that part of the Sandsuck shale referred to herein, but its stratigraphic relations are not yet fully understood.

The Sandsuck shale was recognized by Keith in a small

area on Chilhowee Mountain, but King's observations (1949, p. 631) indicate that it is actually more extensive. King's conclusions as to its thickness, character and extent are adopted in this paper.

Swingle's descriptions and thicknesses of formations (1949) in the Chilhowee group are used. He distinguished the Helenmode member of the Hesse quartzite in the Miller Cove area. This unit was first recognized in northeastern Tennessee by Stose and Schrader (1923, p. 25) as a set of transition beds between the Erwin quartzite and the Shady dolomite, and was later named the Helenmode member of the Erwin quartzite by King *et al.* (1944, p. 31) for exposures in that area.

Stose and Stose (1949, pp. 299-300) recognized that the Shady dolomite and the Rome formation occur in Miller Cove, and lie in normal stratigraphic succession on the rocks of the Chilhowee group.

Within the Ordovician section departures from older practices are as follows: (1) The term Mosheim and Lenoir limestones linking demonstrably contemporaneous facies (Cooper and Cooper, 1946, p. 52), is used in place of Keith's (1895) Chickamauga limestone. (2) The term Middle Ordovician shale is frequently used in the following discussions as a collective term including Athens shale, Tellico sandstone, and Sevier shale. These older terms have not proved natural subdivisions in detailed work, and a reclassification is under consideration by the present author.

Northern trace of Great Smoky fault and nearby faults.—Along the northwest face of Chilhowee Mountain Cambrian or Precambrian rocks are faulted over Middle Ordovician shales and calcareous sandstones and slices of limestone of the Knox group. East of the end of the mountain the fault swings southwestward into the valley of the West Fork of the Little Pigeon River, which it follows for 2 miles. It then curves back to a northeastward strike, closely paralleling the top of the Knox group that lies in an anticline to the north.

Three road cuts expose the fault plane itself. One is between Sugarloaf Mountain and Little Pine Mountain (fig. 2, loc. A), where quartzite of the Cochran formation overlies Middle Ordovician shale. At the mouth of Yellow Spring Hollow (fig. 2, loc. B) and at the head of Possum Hollow (fig. 2,

TABLE 1

Generalized Stratigraphic Sequence

System, Series or Group	Formation or Member	Thickness (feet)	Character
Mississippian	Newman limestone	1,500	Calcareous shale and argillaceous limestone; sandstone and red shale at base.
	Grainger shale	900	Gray sandy shale, sandstone and conglomerate
Devonian or Carboniferous	Chattanooga shale	25	Black shale
Ordovician	Bays formation	400	Red mudrock and white sandstone
	Sevier shale Tellico sandstone Athens shale	6,500	Six calcareous sandstone units interbedded in calcareous shale; black calcareous shale at base. Here collectively termed Middle Ordovician shale.
	Mosheim and Lenoir limestones	100	Dove-gray, aphanitic, and dark-gray, argillaceous limestone
Knox group	Undivided	2,000	Light-gray limestone; minor amounts of dolomite; some sandy beds and shaly seams
	FAULT: SEQUENCE BROKEN		
Cambrian	Rome formation	500	Red shale and silty shale
	Shady dolomite	1,000	Gray, thick-bedded to platy dolomite
Chilhowee group	Helenmode mem.	200	Green siltstone and dolomitic sandstone
	Hesse quartzite	1,000	White, fine- to coarse-grained quartzite
	Murray shale	500	Blue-gray, brown-weathering, sandy shale
	Nebo quartzite	150	White, fine- to coarse-grained quartzite
	Nichols shale	400	Blue-gray, brown-weathering, sandy shale
	Cochran formation	1,000	White, fine- to coarse-grained feldspathic quartzite with a few conglomerate beds; red sandstone and shale in lower half
Precambrian Ocoee series	Sandsuck shale	4,000	Gray, brown-weathering, micaceous shale with interbedded impure limestone, conglomerate and sandstone
	— — — RELATIONS UNKNOWN — — — — — — — — — —		
	Sericite phyllite	?	Silvery-gray, finely laminated, very fine-grained sericite phyllite

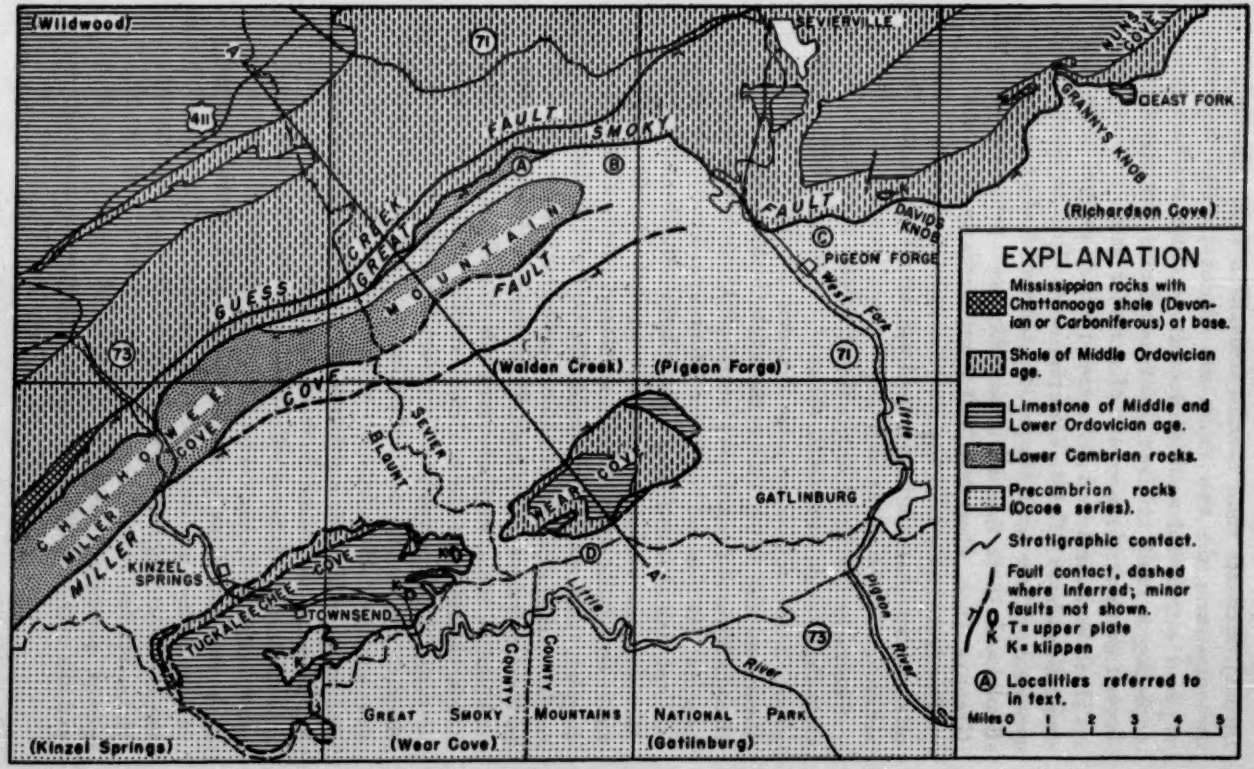

Fig. 2. Outline geologic map of parts of Great Smoky Mountains and Appalachian Valley, eastern Tennessee. Names enclosed in parentheses refer to T. V. A. 7½ minute quadrangle maps.

loc. C) Sandsuck shale overlies Ordovician shale. At the last two exposures the two shales dip almost parallel and are exposed within inches of each other, so that unless one is expecting a fault at these points, or knows the rocks well, he will overlook the presence of a major fault.

These exposures and its mapped trace suggest that the fault dips about 45° SE. Variation of its dip is shown by the presence of three small klippen, the largest of which is Davids Knob, and three flaplike areas, the most prominent being Grannys Knob, where the fault plane is nearly horizontal.

The fault has a bold topographic expression where quartzite overlies shale, but no expression at all where two very similar rocks are in contact.

The rocks northwest of the Great Smoky fault are Middle Ordovician shale with small slices of limestones of the Knox group intervening in places. Between the Little Tennessee River and the Little River the shale forms a narrow belt that in turn is faulted over rocks of Mississippian age, exposed at the foot of Chilhowee Mountain. This second fault is here named the Guess Creek fault. Northeastward the Mississippian rocks are cut out against the Guess Creek fault at a point about a mile southwest of the Little River. Beyond, the fault lies within Middle Ordovician shales, those to the southeast of this fault being approximately equivalent to the lower third of the homoclinal sequence to the northwest.

About 5 miles west of Sevierville the Guess Creek fault enters the valley of Guess Creek, which it follows for 3 miles eastward, lying parallel to Tennessee Highway 71. Ordovician shales in the vicinity of the fault are exposed along this highway for about 12 miles west of Sevierville; these are thrown into many small folds and faults, mostly of minor significance.

Along the southeast limb of the anticline that lies east and southeast of Sevierville the Great Smoky fault trends nearly parallel to the contact between the Middle Ordovician shale and the Knox group. Through part of this distance Middle Ordovician shale forms a narrow belt in which low-angle faults suggest a telescoping of the section. At other places the fault very nearly approaches the top of the Knox group, producing complex slicing that repeats the Knox and the overlying Mosheim and Lenoir limestones as many as

four times. In the Nuns Cove area, where the Great Smoky fault is in contact with the limestones, the limestones are repeated several times and are lightly mineralized.

Along the entire mapped trace of the Great Smoky fault are small slices of limestones of the Knox group, the largest of which is west of East Fork. The rocks in these slices are shattered, but they resemble lithologically the Mascot limestone or highest limestones of the Knox group, a suggestion confirmed by the occurrence of *Diparelasma* sp. in the slice on the south bank of the Little River.

The Nebo quartzite is in contact with Middle Ordovician shale along the Great Smoky fault 4 miles southwest of the Little River; northeast of that point the Nichols shale lies next above the fault, and progressively lower formations appear as the fault is traced northeastward. Still farther northeast Ferguson distinguished slices of the Cochran formation between the Ordovician rocks and the Sandsuck shale. East of the West Fork of the Little Pigeon River the stratigraphy of the Ocoee series is less well understood, but it is known that different units are in contact with the fault at different places.

The Miller Cove fault lies about 2 miles southeast of and nearly parallel to the Great Smoky fault in the vicinity of Chilhowee Mountain. This break is most strikingly displayed along the southeast side of Miller Cove, where the Sandsuck shale is faulted against the Rome formation and Shady dolomite. These relations, and Keith's structure sections (1895), led Wilson (1935) and other authors to suggest that the Miller Cove fault is in fact the main Great Smoky fault. However, the Shady dolomite and the Rome formation are cut out by the fault at the northeast and southwest ends of Miller Cove, and to the northeast the fault cuts down to the Sandsuck shale, making it difficult to trace, and indicating a decrease of throw. The Miller Cove fault thus seems to be a relatively minor break in the thrust sheet above the Great Smoky fault.

Cove areas.—Wear, Tuckaleechee, and Cades Coves, and a small area at Calderwood lie in the windows previously referred to. Work is now in progress in these areas, so that many details are not yet available.

At Calderwood and Cades Cove, limestone is in contact with allochthonous rocks of the Ocoee series. According to Safford (1869, p. 188) the limestones and dolomites of Tallassee Cove (the Calderwood window) "show by fossils that they belong to the lower part of the Nashville formation (the Nash) and the upper part of the Knox." This early report of Middle Ordovician fossils at this locality has not since been verified. The limestone in Cades Cove has yielded fossils proving it to be of Longview age (Neuman, 1947). Perhaps 1,500 feet of rocks of the Knox group has therefore been faulted away in addition to the towering section up through the Carboniferous.

Wear and Tuckaleechee Coves have two points in common that contrast sharply with Calderwood and Cades Cove: (1) The uppermost limestones of the Knox group, the Mosheim and Lenoir limestones, and the lowest Middle Ordovician shales are exposed in continous section at a few localities in both areas. (2) A discontinuous ring of slices of the Knox lies beneath the allochthonous Ocoee rocks and above Middle Ordovician shales.

The floor of Wear Cove is formed on an irregular dome of limestone of the Knox group, surrounded by Mosheim and Lenoir limestones, and Middle Ordovician shale. The shale ring is complete in all but the southeastern corner, where it is overlain by a fault slice of limestone of the Knox.

The structure of the limestones in Tuckaleechee Cove is the subject of current investigation. At this stage of the investigation it can be stated that: (1) most if not all of the Knox group in Tuckaleechee Cove contains fossils typical of the Mascot limestone (*Ceratopea* sp., *Diparelasma* sp.); (2) where cliffs afford large exposures, complex structures may be seen that suggest the piling up of thin fault slices of the limestone; (3) the central limestone body of the Cove is almost completely surrounded by a narrow belt of Middle Ordovician shale, which for the most part is not in normal stratigraphic sequence on the Knox, *i.e.*, the Mosheim and Lenoir limestones are missing in most places, and Middle Ordovician shale lies directly on limestone of the Knox group, with considerable fracturing that suggests movement at the contact.

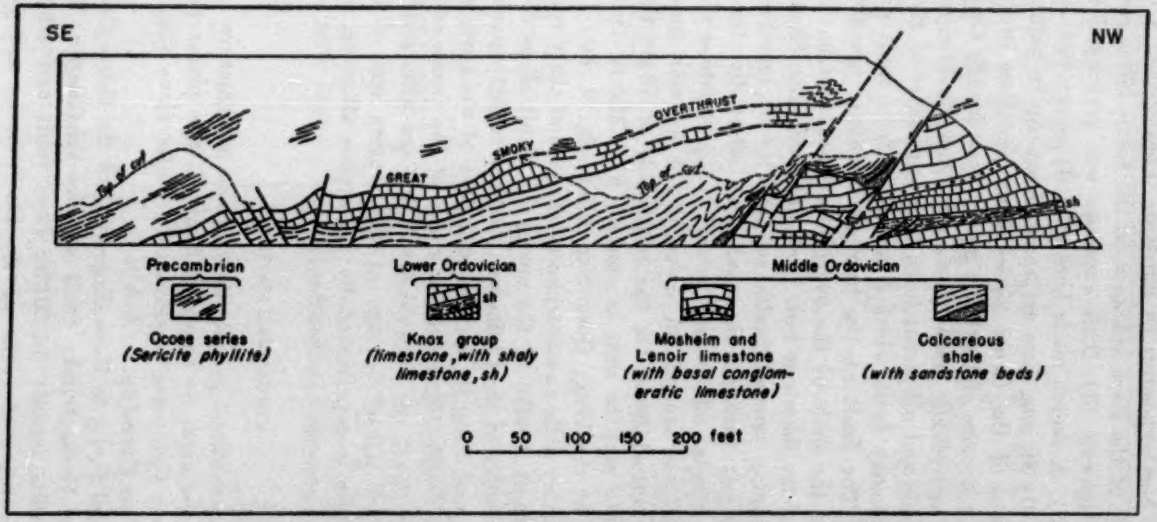

Fig. 3. Sketch showing Great Smoky fault as exposed in road cut and higher slopes, on southwest side of Tennessee Highway 73 at the east end of Tuckaleechee Cove, 0.2 mile northwest of entrance to Great Smoky Mountains National Park. By P. B. King and members of Great Smoky party.

One of the best exposures to illustrate Tuckaleechee Cove is just outside of the Park entrance on the Little River road (Tennessee Highway 73). This exposure was first cited by Wilson (1935). A sketch made here (fig. 3) shows two sets of faults. Gently dipping ones set apart, from top to bottom, sericite phyllite of the Ocoee Series from limestone of the Knox group; limestone of the Knox group from Middle Ordovician shale; and Middle Ordovician shale from Mosheim and Lenoir limestone and subjacent beds. The uppermost of these is the Great Smoky fault, which is underlain by a fault slice of limestone. The fault at the base of the shale truncates sandy beds in the shale of the overriding block, and has removed some of the limestone beds from the overridden block.

Steeply dipping normal faults cut the lowest limestones and may project through the shale and offset the Great Smoky fault. Similar offsets may be seen in the limestone slice.

The allochthone around the coves is not as well understood as the autochthone. On the south side of Wear Cove sericite phyllite may be seen in contact with Middle Ordovician shale on the Wear Cove Gap road (fig. 2, loc. D), whereas relatively little metamorphosed sandy and shaly rocks lie near the fault 2 miles to the northeast. Fault slices composed of quartzites of the Chilhowee group were distinguished by Ferguson and King in the southern part of the cove, adjacent to the fault. Allochthonous rocks of the Ocoee series in the eastern part of Tuckaleechee Cove are also sericite phyllite, but at Kinzel Springs at the western end of the Cove, the Ocoee is represented by calcareous siltstone, apparently belonging to the Sandsuck shale.

STRUCTURE SECTIONS

Surface observations permit construction of structure sections across the area. As shown in figure 1, two places were chosen—across Chilhowee Mountain to Cades Cove (fig. 4, B-B′) and Wear Cove (fig. 4, A-A′).

The essential faults in these diagrams are the Guess Creek fault and the Great Smoky fault and its subsidiaries. The subsidiary faults include the Miller Cove fault and others. Structural features of rocks of the Ocoee series are generalized.

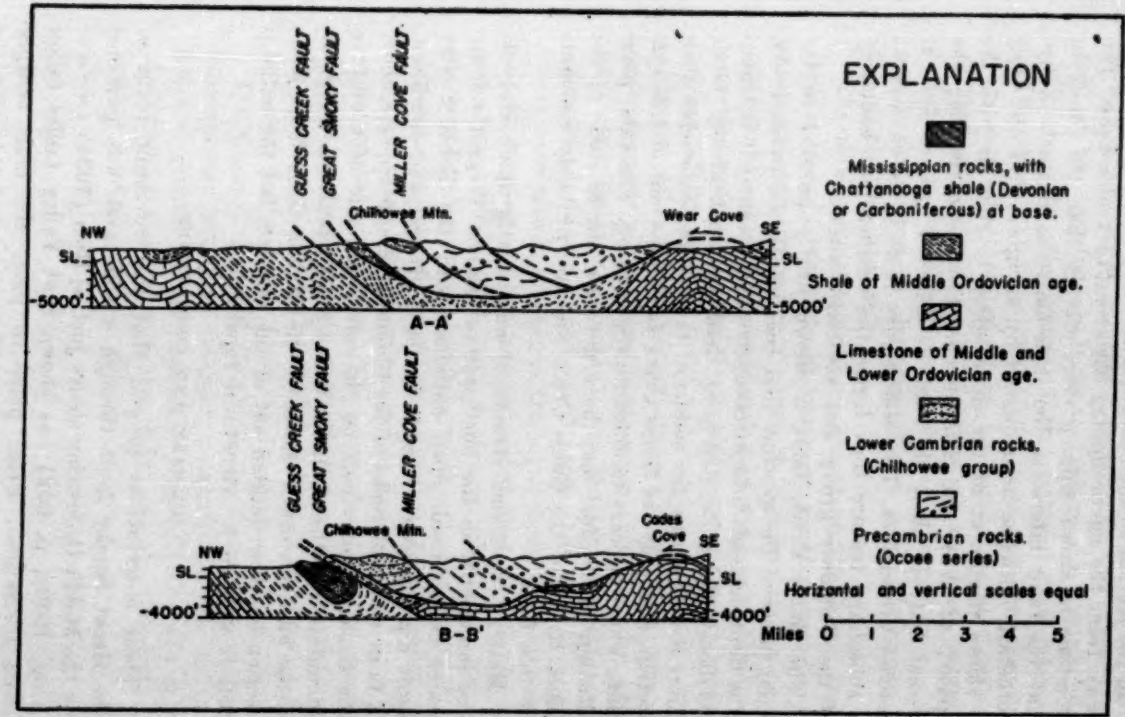

Fig. 4. Structure sections along lines indicated on figure 1.

In the section to the southwest the Great Smoky fault dips away from the north-dipping limestone of Cades Cove. The limestone is shown dipping more steeply than the fault, so that the fault intersects the shale-limestone contact. A hypothetical anticline accompanied by an upwarp of the fault is shown northwest of the shale infold to coincide with the upwarp of Wear and Tuckaleechee Coves. On reaching the second body of shale the fault is deflected upward until it reaches the surface. The Miller Cove fault is shown here as a subsidiary feature that forms the southeastern boundary of the Chilhowee group and associated rocks.

The Guess Creek fault is shown nearly parallel to the axial plane of the syncline that encloses Mississippian rocks. The fault descends into successively older rocks as it is traced northeast along its strike, so that northeast of the Little River it cuts across the middle of the Middle Ordovician shale section. Probably the Guess Creek fault grew out of this syncline, which appears to antedate the faulting. The axial plane cleavage of the fold may have governed the attitude of the fault. Rocks of the Guess Creek slice are probably remnants of this fold.

Most of the same structural and stratigraphic elements are intersected in the northeastern section. Wear Cove appears as a broad, open anticline, with the Great Smoky fault dipping away from it to the northwest and southeast. A fault wedge of rocks of the Chilhowee group appears above the Great Smoky fault on the northwest side of Chilhowee Mountain. Northwest of the Great Smoky fault Mississippian rocks and the upper third of the Middle Ordovician shale section has been faulted out of the syncline, but the outcrop belt is widened by structural repetition.

SUMMARY AND CONCLUSIONS

These observations suggest that the movement plane of the Great Smoky fault through a wide area was governed by the Middle Ordovician shales just as Rich (1934) (*see also* King, 1950a, p. 642) has shown that Valley faults follow shale formations. From place to place the fault scraped away its shale lubricant, with the result that thin slices of limestone were piled up, as in the Grannys Knob area and

Tuckaleechee Cove. The slicing in these areas where the shale is very thin and the relative simplicity of the outcrop pattern of the limestone-shale contact where there is abundant shale show the effectiveness of this material as a lubricant.

The absence of limestones higher than the Longview limestone in Cades Cove might be explained by the proximity of that area to the point of origin of the fault, where it had not yet found a horizon of easy gliding, or perhaps was in the process of changing from a lower horizon to the top of the Knox group.

The total stratigraphic displacement on the Great Smoky fault exceeds 10,000 feet. The minimum northwestward movement, determined by the windows, is 8 miles. In the course of forward motion the overthrust mass may have ridden for some distance on the Rome formation southeast of the present outcrop of the fault.

On the other hand, the allochthone in contact with the fault suggests no preferred horizon; in fact a section about 3,000 feet thick is in contact with the fault from place to place on the face of Chilhowee Mountain alone. Sharp contrasts have also been seen in the allochthone that surrounds the windows. It is therefore suggested that the allochthone possessed a folded and faulted structure prior to its emplacement in its present position relative to the autochthone. Furthermore, the southeastern part of these folded and faulted rocks was altered by low-grade regional metamorphism before emplacement by faulting. Two orogenies are not implied. Rather, it is suggested that the deeper rocks were deformed during an earlier stage of the Appalachian orogeny, before they were broken away from the basement.

The Guess Creek and Great Smoky faults are probably synchronous, but their different patterns are due to their different genetic backgrounds. The Guess Creek fault is the local manifestation of a broken fold, and the Great Smoky fault is a major crustal rupture.

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A MACROSCOPIC METHOD OF FABRIC ANALYSIS

R. H. CLARK and D. B. McINTYRE

ABSTRACT. The study of a rock is not complete unless the nature and orientation of its fabric have been determined. The whole fabric of a rock cannot be determined without the use of the universal stage, for the crystal lattices may have a preferred orientation which cannot be detected macroscopically. For this reason many petrologists, lacking the necessary apparatus, make no attempt to analyse the fabrics of the rocks which they are investigating. The object of this paper is to describe a rapid and accurate method of macroscopic fabric analysis that is applicable to a large variety of rocks, and that requires no complex equipment; indeed, it is often possible to use the method directly in the field. If the lattice fabric can be detected only by optical methods, the universal stage must, of course, be used. The danger of reaching erroneous conclusions by using insufficient data is pointed out. In view of the simplicity of the method and its widespread applicability, it is suggested that it should be used to complete routine petrological examination of a rock.

NOMENCLATURE

DISCUSSION of the terminology will be found in Knopf and Ingerson (1938), Fairbairn (1949), and Clark and McIntyre (1951). For the purpose of this paper, the following definitions are adopted:

The *fabric* of an object is described by all the spatial data (fabric elements) which it contains. A rock is said to have a *simple fabric* when it contains a single fabric element (*e.g.* lineation or plane). A rock is said to have a *compound fabric* when it contains more than one fabric element (*e.g.* lineation + plane; 3 planes; etc.).

A *face* is an exposure-plane, either natural or artificial.

A *trace* is the intersection of a fabric element with a given plane.

Pitch is the angle, measured in some specified plane, between a lineation, or a trace, and the horizontal.

Plunge is the vertical angle between a lineation, or a trace, and the horizontal.

Trend is the strike of the vertical plane containing a lineation or a trace.

In this paper the writers are concerned only with the geometric analysis of the fabric; the genesis of the fabrics discussed is not dealt with. For example, the origin of even a "simple" fabric is commonly far from simple.

INTRODUCTION

In the course of a structural investigation of the macroporphyritic basalts of Arthur's Seat, Edinburgh, one of the writers (Clark) encountered considerable difficulty in determining whether the fabric was linear or planar. The method used was that developed by Hans Cloos (see R. Balk, 1937). The direction of preferred orientation of the macro-phenocrysts is determined in the field on two or more faces of an outcrop, and the nature and orientation of the structure responsible for these traces is estimated by eye. Provided that only a planar structure is present, this method is satisfactory, being both simple and reasonably accurate. However, in localities where lineation may be present, visual determination of the structure is not practicable unless the exposures are unusually perfect.

Balk (1937, pp. 139-155) suggested, although in different terms, that strength of trace might be used as an aid to fabric analysis. Unfortunately, in many outcrops degree and nature of weathering play an important role in determining the apparent strength of a trace. Moreover, in the field, the number of suitable faces is rarely sufficient for the fabric to be determined by eye with complete confidence.

If traces can be measured with reasonable accuracy on a minimum of three suitable, non-parallel faces, although a larger number is to be preferred, the nature and space orientation of the structure responsible can be determined with the aid of a stereographic projection. Should sufficient suitable field exposures be lacking, an oriented hand specimen can be collected, and the required number of faces cut or ground upon it. The fabric can then be determined by analysis of the traces observed on these faces.

THE USE OF THE STEREOGRAPHIC PROJECTION[1]

Fabric may be planar, linear, or cylindroidal, but the last is rarely developed on so small a scale that the curvature of the traces is noticeable in a single hand specimen or small outcrop, except in the case of metamorphic rocks. For this

[1] Like all structural geologists who use the stereographic projection, the writers owe a debt to Professor Bruno Sander, the pioneer of modern fabric studies. Readers unfamiliar with the use of the projection should refer to the useful article on the subject by W. H. Bucher (1944).

reason, only linear and planar fabrics are considered here. An interesting example of a cylindroidal fabric, developed on a macroscopic scale in an igneous rock, has been described by Tomkeieff (1946).

1. *Simple Fabrics.*—If the structure is planar, the traces on random faces are the intersections of the planes with these faces. In this case all traces have one common feature: *viz.* they lie parallel to the structure planes. Any two traces define the space orientation of the planar arrangement; the remainder must all lie in this plane. Thus in a stereographic projection, the poles of the traces must lie upon the great circle representing the planar structure.

If the structure is linear, the traces are the projections of the lineation upon the faces studied; *i.e.*, any trace is the intersection of the exposure face with the plane which contains the lineation and which is normal to the exposure face. If the orientations of the faces and traces are known, the great circles representing these normal planes are easily constructed

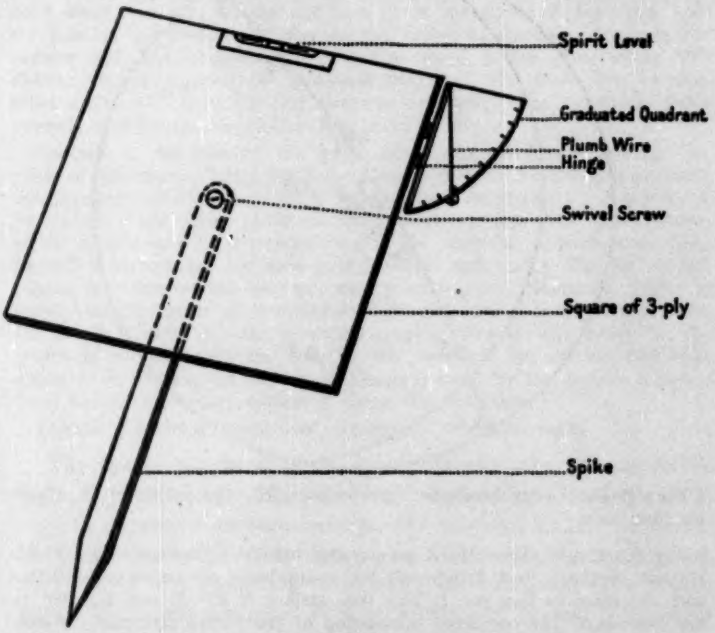
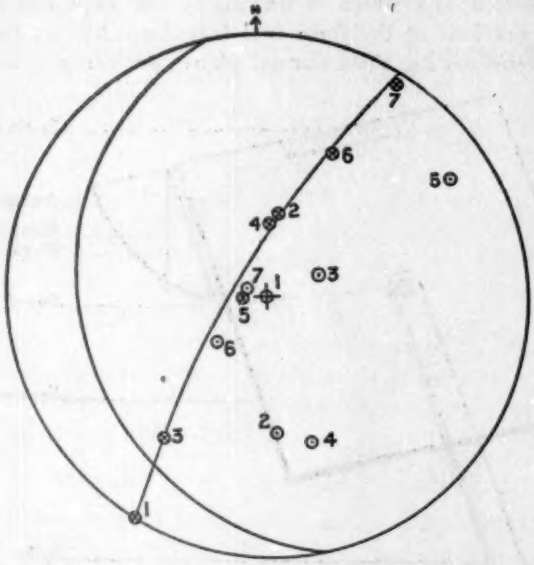


Fig. 1. Apparatus to assist field determination of fabric.

on the projection. The point at which these great circles intersect is the pole of the lineation (Lowe, 1946).

To determine the nature and orientation of the fabric elements in an outcrop or hand specimen, it is necessary to know the strike and dip of each face, and the pitch of the trace upon it. These data are plotted on the projection. If the poles of the traces lie upon, or are close to a great circle, then the fabric is probably planar (fig. 2.). The great circle may be constructed and its strike and dip read directly from the projection.

Should the traces not lie on a great circle, lineation may be suspected, and the normal planes referred to above must be constructed. For each exposure surface, and for each trace, the required normal plane is represented by the great circle containing the pole of the trace and the pole of the face on



Figs. 2—8. Lower hemisphere projections. ⊙₁ Pole of face; ⊕₁ Trace on that face.

Fig. 2. Single plane. Macro-porphyritic basalt of Dunsapie-type, Lion's Haunch, Arthur's Seat, Edinburgh. For convenience, the traces were plotted with reference to face no. 1. This face strikes N 62° E and dips 68° to the south-east. The corrected orientation of the planar structure, relative to the horisontal, is shown by the heavy great circle.

which that trace was observed. If these great circles, representing the normal planes, intersect at or near a point, then the fabric is linear and the trend and plunge of the lineation can be determined (figs. 3 and 4).

Example. An oriented specimen of macro-porphyritic basalt (fig. 3) had six faces cut and ground upon it, and traces were marked upon each face. The following orientations of faces and traces were recorded:

Face	*Strike*	*Dip*	*Pitch of Trace*
1	—	0°	106° E of N (trend)
2	168°	85°E	45°N
3	45°	90°	44°SW
4	157°	80°W	46°N
5	53°	85°SE	50°SW
6	134°	18°SW	36°NW

Plotting procedure: A sheet of tracing paper is laid over a Wulff stereographic net; centre and north points are marked by a cross and an arrow respectively.

Face 1. As this face is horizontal the normal to it is vertical, and its pole lies at the centre of the net. The pole of the trace on this face is at the circumference, 106° east of north.

Face 2. The tracing paper is rotated until the north arrow on it is 168° in an anticlockwise direction from the north point of the net. The north-south meridian on the net then gives the strike of the face, and the pole of the face-normal lies on the east-west diameter, 5° from its eastern end. The projection of the face itself is the great circle 90° distant measured along the east-west diameter. The trace lies on this great circle, 45° from its north-western extremity. The remaining face-normals and traces are plotted in a similar way.

Analysis of the fabric: No great circle can be drawn through the poles of the traces; hence the fabric is not planar. Normal planes must now be constructed. The paper is rotated until face-normal 1 and trace 1 lie on the same great circle on the underlying net. This great circle, which in this case is a straight-line, is the required normal-plane. This procedure is repeated for each pair of faces and traces. The six normal planes thus constructed intersect nearly at a point. Hence the fabric is linear, and the point of intersection represents the pole of the lineation. Its trend is given by the diameter passing through the point. If the paper is rotated until the pole of the lineation lies on the east-west diameter of the net, the amount of plunge is given by the angular distance from the circumference measured along this diameter.

Result: Lineation, trend 106°; plunge 30° down to west.

The traces produced by a linear fabric may chance to lie near a great circle. This is particularly likely to happen if several exposure surfaces are nearly parallel to the lineation. For this reason normal planes should always be constructed, as a "test" for lineation, even when the existence of a planar structure seems obvious. If any ambiguity should remain, it is necessary to cut control faces with selected orientations,

e.g. one in the suspected plane and another normal to the possible lineation.

The stereographic projection should be regarded as a "structural tool" rather than as an infallible geometric construction. On completing the construction, the specimen must be re-examined to ensure the absence of traces on faces parallel to a planar or normal to a linear arrangement. Traces on faces nearly normal to a lineation should show random orientation of platy minerals, and cross sections of prismatic crystals. Surfaces almost parallel to a purely planar structure should contain a large proportion of flat surfaces of platy crystals, with a random orientation of their long axes, and/or the long axes of prismatic crystals with random orientation.

The projection furnishes information as to which faces can be expected to be unreliable. If lineation has been correctly determined, then, unless some of the crystals are unusually transparent, poles of faces on which traces have been measured will not lie near the pole of the lineation; the latter will lie close only to those poles representing faces on which no trace could be found (fig. 4, faces 2 and 5). Conversely, traces

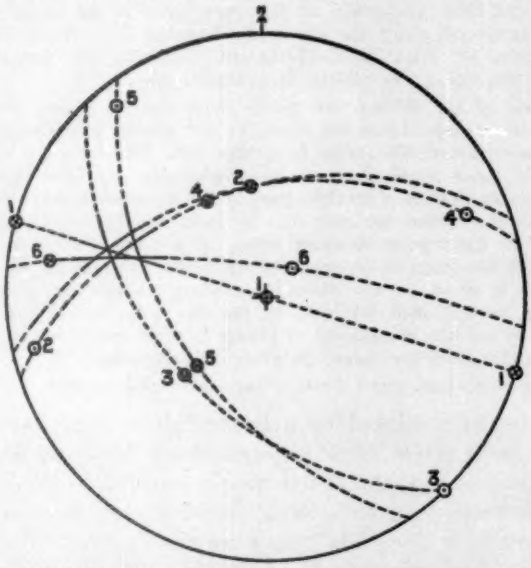


Fig. 3. Lineation. Macro-porphyritic basalt of Dunsapie-type, Lion's Haunch, Arthur's Seat, Edinburgh.

will be strongly developed on faces whose poles are 90° from the pole of the lineation. With a planar fabric, on the other hand, the nearer the pole of the face lies to the great circle of the fabric plane, the stronger the trace upon that face will be.

It may be remarked here that faces cut upon a hand specimen are analogous to perfect natural exposures. The relative strength of the traces on them depends solely on the nature of the fabric and its orientation with respect to the observation surfaces. The effect of directed weathering has been eliminated.

2. *Compound Fabrics.*—In some specimens of certain rocks, particularly metamorphic rocks, granites, and micro-porphyritic basalts, more than one trace may be clearly recognised on some or all of the faces. In such cases the fabric is compound. Two traces may be produced by two lineations, two planes, or a plane with a lineation either on or off it, and still more complex combinations occur; but fabric analysis is still comparatively simple if a sufficient number of measurements are accurately made and carefully plotted. Two traces

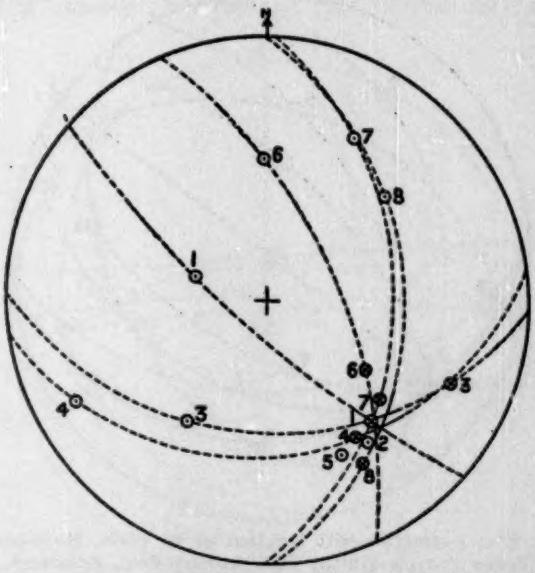


Fig. 4. Lineation. Amphibolite ("Lewisian"), An Sguman, Fannich. The absence of traces on faces 2 and 5 is to be expected, for these are almost normal to the lineation.

on a single face cannot both be produced by the same fabric element, and this most important point must be kept in mind while the determination is being made.

Example 1. Fig. 7.

A specimen has six faces, of which five display two traces and the sixth, one. The poles of the eleven traces fall into two groups. Six, each from different faces, lie upon one great circle, and six upon another great circle. Intersections of normal planes are widely scattered. The fabric therefore consists of two planes. The face yielding only one trace, face 3, contains the line of intersection of the two planes.

Example 2. Fig. 6.

A specimen has six faces, each with two distant traces upon it. When the twelve traces are plotted it is found that the poles of six of the traces, no two of which are from the same face, lie near a great circle. The normal planes containing these six traces intersect at widely scattered points, but the normal

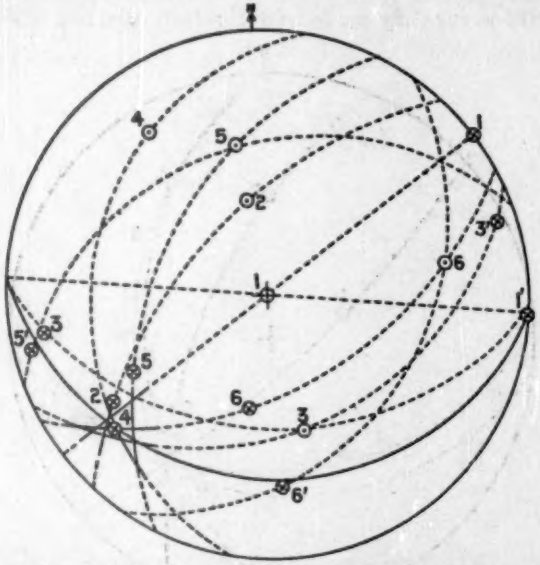


Fig. 5. Planar structure with lineation on the plane. Micro-porphyritic basalt of Jedburgh-type, Whinny Hill, Arthur's Seat, Edinburgh. Normal planes have been constructed through all traces; those through traces produced solely by the planar structure intersect at random. Faces 4 and 2 contain the lineation; hence the traces of plane and lineation coincide.

planes which contain the other six traces (1, 2, 3, 4, 5′, 6′) intersect near a point. Hence the fabric consists of a plane and a lineation. One of the traces observed on each face was that of the plane; the other, that of the lineation. In this case, the lineation is normal to the plane.

For a case where lineation lies in the plane, see figure 5.

Example 3. Fig. 8.

A specimen has seven faces. Four of these contain two traces; the remaining three contain one single trace. It is found that no great circle can be drawn through the poles of any seven traces from different faces. The eleven normal planes appear at first to intersect at random on the projection, but, on careful examination, it is found that seven of them intersect near one point, and six near another point. Each of these groups comprises normal planes which contain traces from different faces. Therefore the fabric consists of two lineations.

PRACTICAL DETAILS

Field Exposures.—When it is desirable to work directly from field outcrops, strikes and dips of surfaces must be

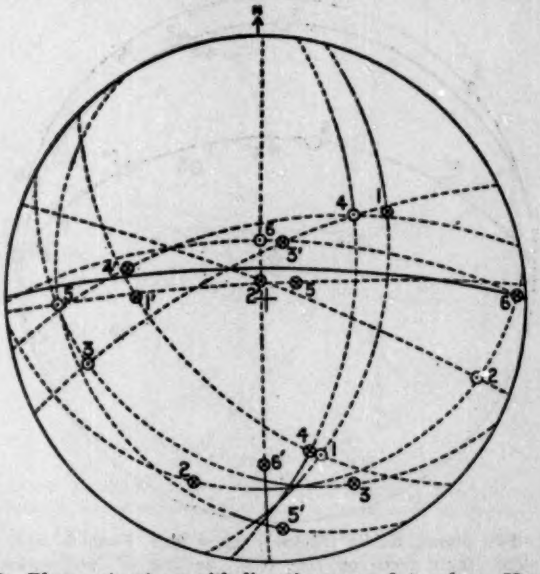


Fig. 6. Planar structure with lineation normal to plane. Hypersthenic rock, Loch Riecawr, Loch Doon.

measured with reasonable accuracy. If faces are smooth, this is simple, but, when they are uneven, an instrument such as that shown in figure 1 is useful. The pitch of a trace is best measured with a protractor and a small spirit level.

Collection of Oriented Specimens.—A suitable specimen should be broken from the outcrop and fitted back into place. North is indicated by an arrow marked upon the upper surface. Two horizontal lines, drawn with the aid of a small spirit level upon two steep surfaces at suitable angles to each other, complete the orientation. The marks should be made permanent as soon as possible by cutting them into the specimen with a diamond wheel.

Facing of Specimens.— Much time is saved if, where possible, faces are cut instead of ground. A horizontal face is not necessary; five or six random, non-parallel surfaces are all that are required. Unless the rock is fine-grained the faces need not be polished. Strike and dip, with respect to the face nearest to the horizontal plane, is measured using the instrument shown in figure 1, with its spike removed.

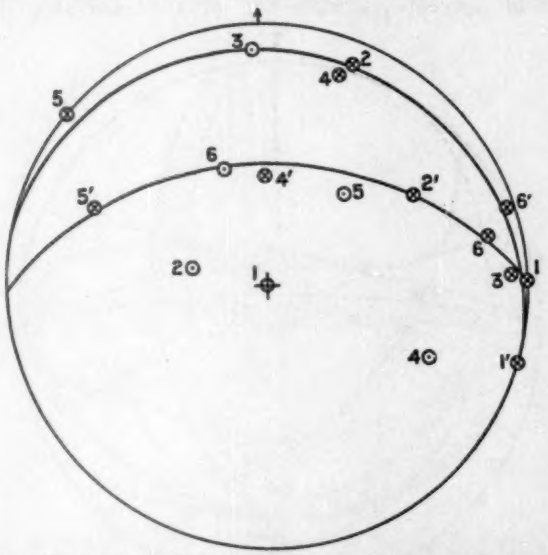


Fig. 7. Two planes. Schist (Moine), Sgurr Mor, Fannich. Specimen not oriented. The single trace on face 3 is the line of intersection of the two planes. The trace of the flatter plane is visible on face 1 because this plane is so strongly developed.

Etching of Faces.—The ease and accuracy with which traces may be determined depend upon the degree of visibility of the oriented minerals. Dark minerals are very easily seen in leucocratic rocks; but in melanocratic rocks, such as basalt, phenocrysts of feldspar and ferromagnesian minerals are barely discernible against the dark groundmass. If such specimens are immersed for some minutes in a moderately dilute solution of hydrofluoric acid, the large crystals become clearly visible. The small crystals of the groundmass are attacked relatively rapidly by the acid, and a gray colour results. Ferromagnesian phenocrysts remain black. The large feldspars become coated with transparent silicic acid; the black rock beneath gives them a dark appearance. Thus, if the rock is washed and kept wet, all phenocrysts appear dark against a light gray background. Traces may be marked with considerable accuracy. If the specimen is allowed to dry, the silicic acid gel on the

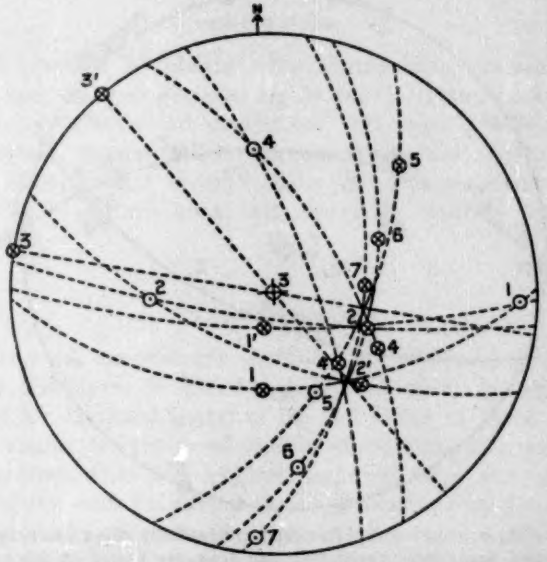


Fig. 8. Two lineations. Porphyritic granodiorite, Glen Fyne. Traces were determined by observing preferred orientations of ferromagnesian crystals. Faces 6 and 7 each display only one trace, for these faces contain the normal to the plane of the two lineations. Face 5 is nearly normal to one of the lineations; the single trace on this face is that of the other lineation.

feldspars forms a white powder (SiO_2), and only the ferromagnesian minerals remain clearly visible. Hence drying should not be permitted until fabric determination is complete, unless, of course, no feldspar phenocrysts are present, *e.g.* in Scottish Carboniferous basalts of Craiglockhart type.

Trace Determination.—In many cases, preferred orientation of crystals on a particular face is obvious at a glance, and the trace or traces may be drawn at once with considerable accuracy. When some of the crystals are transparent, the others are often seen in three dimensions. Sometimes the direction is not so clear, and considerable care must be exercised. The face should be observed from all directions; if doubt remains, no trace should be recorded. Fine-grained rocks, such as micro-porphyritic basalts, should be lightly etched and then examined under strong light with a hand lens

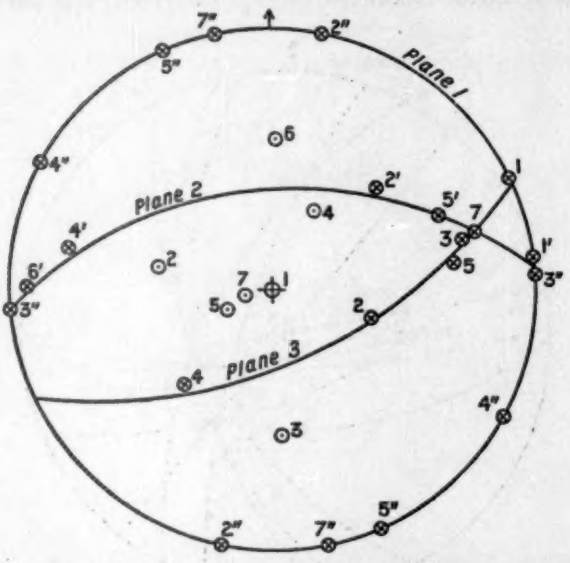


Fig. 9. Three planes. Graphite schist (Dalradian), Glen Livet. Specimen not oriented. The fabric was determined from the traces on faces 1 to 6. Subsequently the space orientation of a face which would contain the line of intersection of the two inclined planes (2 and 3) was predicted from the projection. This face (no. 7) has been ground; one of the traces on it lies on the intersection of planes 2 and 3. It may be noted that planes 2 and 3 are very nearly symmetrically inclined with respect to plane 1.

or binocular microscope of low power. If the rock is very fine-grained, oriented sections may be necessary.

Relating the fabric to the horizontal.—When the orientation of the fabric has been determined with respect to a non-horizontal face, the true strike and dip of this face must be found so that the orientation of the fabric can be related to the horizontal plane. This is most simply accomplished with an instrument similar to that designed by Knopf and Ingerson (1938, plate 20, fig. 2). This may be constructed with two pieces of three-ply and the universal joint of a camera tripod. The specimen is clamped on the upper board with elastic bands, and the board moved until the horizontal marks on the specimen are restored to the horizontal. Strike and dip of the board are measured, and the appropriate correction applied to the projection.

CONCLUSIONS

It is possible to obtain with considerable precision the nature and space orientation of the fabric of any rock which contains a definite and continuous structure. If the fabric is indistinct, so also will be the traces. As the only possible source of significant error need be the determination of the traces, it is obvious that this should be carried out with great care.

ACKNOWLEDGMENTS

Interest in macroscopic methods of fabric analysis was greatly stimulated in Edinburgh by the visit, during 1948-1949 of Dr. Gerhard Oertel of the University of Bonn. It was in the course of structural studies undertaken as a result of this interest, that the method described here was evolved. The writers wish to record their indebtedness to Dr. Oertel for introducing them to this aspect of tectonics. They also wish to thank Mr. J. Dennis and Mr. D. J. Hooten for several valuable suggestions which have been incorporated in the paper.

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University of Edinburgh
Edinburgh, Scotland

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NOMENCLATURE OF EPIDOTE ROCKS

PETER T. FLAWN

ABSTRACT. Rocks composed mostly of epidote result from a number of different geologic processes. Terminology dealing with such rocks is confused, and definitions contain limiting conditions of origin that are objectionable. A review of terminology shows that the terms *unakite* and *helsinkite* can have no general application and are intrinsically undesirable. The term *epidosite* suffers from a number of definitions that impose restrictions on mode of origin and occurrence. As originally defined and as generally used, the term *epidotite* is a satisfactory descriptive petrographic term that demands no special mode of origin or occurrence.

TWO descriptive petrographic names and two geographic petrographic names have been applied to rocks composed mostly of epidote: (1) the French term *epidotite;* (2) the German term *epidosit* (from which the English form *epidosite* was subsequently derived); (3) the term *unakite,* taken from Unaka Range on the border of North Carolina and Tennessee; and (4) the term *helsinkite,* taken from the Finnish city of Helsinki. The term *saussurite* prefixed to rock names (*e.g.,* saussurite-gabbro) has a special meaning that does not concern us here.

Definitions of epidotite.—(1) the term *épidotite* was originated by Cordier (1868, p. 153) who defined it as follows:

> Roche stratiforme, *composée d'épidote* soit grenue, fibreuse ou prismatique, soit plus ou moins a l'état compacte; de couleur communément vert-pistache.

As accessory minerals Cordier lists quartz, calcite, talc, amphibole, garnet, feldspar, sphene, pyrite, magnetite, chromite, etc. He notes the occurrence of epidotites in thin beds or reniform masses in metamorphic terranes (" . . . dans les terrains primitifs stratifiés."). Although Cordier's notebooks (1868, p. 154) show that his observations pertained to epidotites of metamorphic origin, his definition is general. He gives *Épidosite, Pistazitkels,* and *Pistacite Rock* as synonyms.

(2) De Lapparent (1923, p. 151) has defined *epidotite* as follows:

> Les épidotites, roches compactes et denses, sont faites d'epidote ou de zoisite associées parfois à des amphiboles (actinote ou hornblende) à des pyroxènes, à du sphène, à de la calcite, à du quartz et à de l'orthose; . . . .

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De Lapparent discusses epidotites as members of the calcium-silicate contact-metamorphic suite. However, he does not restrict the term to contact-metamorphic rocks and, discussing glaucophanites (1923, p. 470), states that when epidote is more abundant than glaucophane the rock becomes an epidotite. De Lapparent might well have referred to amphibolites in general and not limited himself to glaucophanites. This definition contains no limiting conditions of origin or occurrence and, with one exception, is essentially a restatement of Cordier's original definition. Cordier, probably because of his experience with epidotites in metasedimentary terranes, included the word *stratiforme* in the original definition. De Lapparent makes no mention of stratification.

(3) Loewinson-Lessing (1901, p. 1085) gives *Epidotgestein* as a synonym for *epidotite* and refers to Inostranzeff (1879, p. 113). Inostranzeff (1879, pp. 112-114, 119-128) distinguishes between *Epidotgestein* and *Epidosit*. He defines *Epidotgestein* as a dark aphanitic rock made up of epidote, remains of oligoclase, hornblende, hematite, and diverse other accessory minerals. Discussing *Epidosit*, Inostranzeff states that he is not using the term in the strict sense of a pure epidote-quartz rock. He found that epidote and quartz were invariably accompanied by actinolite (in his area) and modifies the definition to include actinolite. Inostranzeff also discusses varieties of "Epidotgestein" and epidosite such as "Chlorit-Epidotgestein" or chlorite-epidosite. (*Gestein* here has a special meaning and *Epidotgestein* cannot be freely translated as *epidote rock*.) "Epidotgestein" is distinguished from epidosite by mineral composition and grade of metamorphism. Both types, according to Inostranzeff (1879, p. 205), are derived from metamorphism (hydrothermal alteration) of diorite: diorite→ epidote-diorite→ "Epidotgestein"→ epidosite.

Definitions of epidosite.—(1) Loewinson-Lessing (1901, p. 1085) credits the origin of the term *epidosite* to Reichenbach (1834, p. 55)[1] and defines the term as follows:

[1]Reichenbach, Karl Ludwig Friedrich, Freiherr von, Geologische Mittheilungen aus Mähren. Geognostiche Darstellung der Umgegenden von Blansko. Vienna. 1834. This report is not listed in any library in this country.

> Roches schisto-crystalline formées d'épidote et de quarz; parfois elles sont grenues, massives.

(2) Holmes (1928, p. 92), likewise referring to Reichenbach, defines *epidosite*:

> Epidosite—a term applied to altered igneous rocks, or veins traversing them, essentially containing epidote and quartz, and generally other secondary minerals such as uralite and chlorite.

This definition differs considerably from the Loewinson-Lessing definition and restricts the rock to a secondary mode of origin.

(3) Zirkel (1893, pp. 374-375; 1894, p. 371) notes three modes of occurrence of epidosite: (a) in calcium-silicate contact-metamorphic suites, (b) in crystalline schist sequences, and (c) as a product of secondary alteration. He states (1894, p. 371):

> Wenn schon im Vorhergehenden Epidot als ein sehr häufiger accessorischer oder wesentlicher Gemengtheil gennant wurde, so gibt es auch zu den krystallinischen Schiefern gehörige Gesteine, welche zum grössten Theil aus diesem Mineral bestehen, wozu sich dann weiter in der Regel noch Quarz oder ein Glied der Amphibolgruppe, Glimmer oder Chlorit gesellen, während Feldspath oder Pyroxen sehr selten zu scheint. Die Structur ist bald ausgezeichnet schieferig, bald mehr richtungslos körnig und namentlich *letztere Vorkommnisse hat man Epidosit gennant.* [Writer's italics.]

A good point in this definition is that the term *epidosite* must apply to massive rocks; schistose epidote rocks are then appropriately named *epidote schists.*

Zirkel (1894, p. 371) discusses epidosites formed by secondary processes:

> Es mag hier daran erinnert werden, dass der Epidot secundär aus manchen anderen Mineralien hervorgehen kann, dass Epidosit auch als Umwandlungsproduct verschiedener, z. Th. eruptiver Gesteine bekannt ist (. . . . von denjenigen Epidositen, welche so als Metamorphosen oder auch wohl gewissermassen als Auslaugungsproducte von Massengesteinen vorkommen, ist daher an dieser Stelle nicht die Rede; eine solche Masse, reiner Epidot mit Quarz, beschrieb z. B. Bergeat von Starvo-Vuni auf Cypern als wahrscheinliches Auslaugungsproduct zersetzter Diabase, ... *Reichenbach erwähnt eine feinkörnige apfelgrüne Epidositmasse an der Grenze des Syenits von Blansko*). [Writer's italics.]

Apparently as originally used by Reichenbach the term *epidosite referred* to epidote rocks of secondary origin.

(4) Cordier (1868, p. 153) credits the term *épidosite* to Pilla (no reference given). Cordier evidently considered the term *épidosite* a French term (note acute accent) synonymous with *épidotite.*

(5) Pilla (1845, pp. 63-65) defines and discusses *epidosite* in an article entitled (in translation) ***Epidosite, A New Rock Type from the Gabbro Family.*** Evidently this article was responsible for Cordier's crediting the origin of the term *epidosite* to Pilla. However, this article postdates Reichenbach's work by 11 years. Pilla lists four varieties of epidosite: granular, variolitic, aphanitic, and earthy. He says:

> Die Charakteristik des Epidosits wäre folgender Maasen festzustellen:
>
> Bestand—Körner von Pistazien-grünem Epidot und von Quarz, bald schärfer geschieden, bald inniger mit einander verschmolzen.
>
> Lagerungs-Verhältnisse: der Epidosit gehort zu den ..... *Gabbro-Gesteinen* und erscheint bald in Gesellschaft der Ophiolithe, bald zeigt er sich dem Granite verbunden.

Pilla contributes some useful observations on the occurrence of epidosite on the island of Elba, but assignment of the rock to the gabbro family was unfortunate. Cotta (1855, p. 74) credits the origin of the term to Pilla and uses his definition.

(6) Rosenbusch (1910, p. 670) defines *epidosite*:

> Epidotfelse oder Epidosit von bald körniger bald schiefriger Struktur . . . . die wesentlich aus Epidot, oft mit night unbeträchtlichem Quarzgehalt und meistens mit etwas Granat, Vesuvian, Titanit, Hornblende usw., bestehen.

This definition is very similar to de Lapparent's definition of *epidotite* and has the merit of being free from genetic implications. Like de Lapparent, Rosenbusch discusses epidosites as rocks formed by contact-metamorphism of impure limestones, but he cites a connection between granular contact-metamorphic epidosites and calcite-epidote schists in the mica schist-phyllite sequence.

(7) Clarke (1911, p. 572) discusses epidosite:

> Epidotization, then, represents a reaction between the feldspars and the ferromagnesian minerals of a rock, and when it is complete a mixture of quartz and epidote remains. Such a rock is known as epidosite and its formation has been many times recorded.

(8) Harker (1932, p. 267) mentions epidote in some Highland quartzites and in granulites of the Moine series. He says:

> An epidote-quartz rock or *"epidosite,"* in which the distinctive mineral bulks largely, is not a common type.

Harker states that most rocks of this composition have a dif-

ferent origin, not related to metamorphism proper. He is probably referring to a secondary origin.

(9) Johannsen (1932, vol. I, p. 250) defines *epidosite* as "a metamorphic rock composed of a mixture of quartz and epidote."

(10) Grout (1932, p. 369) classes *epidosite* as a special term under the heading *Metamorphic Carbonate and Carbonate-Silicate Rocks* and does not refer to epidosites formed by alteration.

(11) Flett (1946, pp. 37-44), describing the petrography of the metamorphic rocks of the Old Lizard Head series, mentions a layered sequence of green schists, mica schists, granulites, and epidosite. He states (p. 40):

> Some of the quartzite bands are so rich in epidote that they become epidosites . . . .

Here the epidote seems to be a primary metamorphic mineral. However, Flett (1946, p. 127) describes also a pillow lava and notes that the central cavity of the pillow is commonly filled with yellow masses of epidosite. The epidote here is certainly of secondary origin, and Flett seems to use the term *epidosite* as a descriptive term only.

Definitions of unakite.—Bradley (1874, p. 519) proposed the term *unakyte* for a variety of granite in which epidote replaces the mica of common granite and the hornblende of syenite. The granite referred to forms part of the Unaka Range of North Carolina and Tennessee. The amount of epidote in the rock is variable and may exceed 50 percent. Pink orthoclase (25 to 30 percent), quartz (about 25 percent), and small scattered grains of magnetite are also present. Phalen (1904) described this rock and noted that all transition stages between unakite and epidosite occur. Watson (1904, pp. 394-398; 1906, pp. 171-174; 1910, pp. 156-159) described the occurrence of unakite in veins that penetrate the granite. He stated that the epidote is secondary and is "derived from the interaction of the ferromagnesian constituent and the feldspar." This is identical with the process suggested by Clarke (1911, p. 572) for the formation of epidosite. Johannsen (1932, vol. II, p. 60) stated:

> There seems to be no doubt but that the unakite originated from the alteration of the associated hypersthene-akerite by

dynamic metamorphism and the percolation of meteoric waters. The chemical analyses and the whole appearance of the thin sections indicate this.

Jonas (1935, p. 51) confirmed the replacement origin of the epidote and showed that it formed through hydrothermal alteration of granodiorite.

By definition unakite is limited in mineral composition, mode of occurrence, and mode of origin. The term can be applied only to a special kind of altered granite.

Definitions of helsinkite.—The term ***helsinkite*** is the European counterpart of ***unakite***. The term was proposed by Laitakari (1918) for dike rocks composed essentially of epidote and albite, ***with epidote considered a pyrogenic mineral.*** The type rock comes from the Island of Hogland in the Gulf of Finland. Asklund (1923, pp. 40-44) noted that similar rocks occur near Stavsjö, Sweden, that contain potassium feldspar and proposed an extension of the term ***helsinkite***. Asklund recommended that the relative amounts of epidote and feldspar be neglected and proposed a ***helsinkite facies*** that specified a magmatic paragenesis of epidote. A magma with a high water content was suggested to explain crystallization temperatures low enough to permit pyrogenic crystallization of epidote. Later papers (Mellis, 1932; Eskola, 1946) argue for a non-pyrogenic origin of the epidote in helsinkite. Eskola (1946, p. 354) states that epidote is a hydrothermal mineral. Barth (1929, pp. 126-127) gives a list of 15 references before 1929 on the helsinkite problem.

This term, like *unakite*, suffers from too many restrictions on mineral composition, mode of occurrence, and mode of origin. There may be some justification in Asklund's proposal of a helsinkite facies (similar to charnockite facies) if the primary paragenesis of epidote in water-rich magmas can be accepted. This is dubious, however, and Johannsen (1937, p. 143) says: "Personally, I am skeptical about primary epidote."

CONCLUSIONS AND SUGGESTIONS

To summarize, rocks composed mostly of epidote occur (1) in contact-metamorphic zones as a result of thermal metamorphism and/or contact-metasomatism of calcium-silicate rocks; (2) in regional metamorphic sequences where epidote is a primary metamorphic mineral or the result of

retrogressive metamorphism (diaphthoresis); (3) in zones of alteration where epidote is a secondary mineral formed by hydrothermal or deuteric action; and (4) possibly by crystallization from a water-rich magma.

It is plain, therefore, that any definition which attempts to limit mode of occurrence or mode of origin is undesirable unless a separate term is proposed for each case. Such a solution results in terms such as ***unakite*** and ***helsinkite*** and presumes that the mode of origin can be positively determined. These terms are of little value outside of the district for which they were originally coined. Researchers who encounter similar rocks usually are forced to modify or extend the original definition. A descriptive petrographic term that makes the mineral composition obvious is eminently preferable if one is readily adaptable. For example, ***epidote-granite*** or ***epidote-granodiorite*** are superior to ***unakite*** where the epidote content of the rock is low, and ***epidotite*** is superior to ***unakite*** where the rock is composed mostly of epidote.

The choice lies between ***epidotite*** and ***epidosite***. Holmes' definition of ***epidosite***, which limits the rock to a secondary origin, has had wide circulation as a reference in the English language. Apparently this definition follows Reichenbach's original usage. If the term ***epidosite*** is to be applicable to rocks of other than secondary origin, it must be redefined. The definitions of ***epidosite*** by Rosenbusch and Zirkel are good and might be combined and restated to make a usable term. It is doubful, however, if another definition would do more than increase the confusion. In the writer's opinion the best solution is to abandon the term ***epidosite*** in favor of the French term ***epidotite*** and modify de Lapparent's definition of the term as follows:

> An epidotite is a compact massive rock composed mostly of epidote (or zoisite) with minor amounts of amphibole, pyroxene, feldspar, chlorite, quartz, sphene, calcite, vesuvianite, garnet, etc.

This follows Cordier's original usage. Moreover, the term ***epidotite*** is more logically derived from ***epidote*** than is ***epidosite***. ***Epidotite*** has been seldom used as other than a purely descriptive term.

The writer has observed that in metasedimentary rocks of the Van Horn, Texas, area, amphibolite grades through epidote-amphibolite to epidotite. The question arises as to

how much epidote is necessary before the rock may be called an epidotite. The writer has found that when the epidote content of the rock exceeds 60 to 70 percent the rock takes on the massive, compact, waxy, yellow-green appearance of the epidotite. However, to set an arbitrary minimum limit is to remove the flexibility of the definition that is given by the phrase *composed mostly of epidote.*

Another problem arises if zoisite and not epidote is the principal rockmaking mineral. Is it then necessary to introduce a new term? The writer believes, following de Lapparent, that it is sufficient to allow for this possibility in the definition of epidotite and thus escape such a term as *zoisitite.* Zoisite is after all a member of the epidote group.

The writer wishes to express his appreciation to Dr. Adolph Knopf, Department of Geology, Yale University, whose remarks prompted the paper and who was kind enough to read the manuscript critically.

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Bureau of Economic Geology
The University of Texas
Austin, Texas

REVIEWS

First Principles of Atomic Physics; by RICHARD F. HUMPHREYS and ROBERT BERINGER. Pp. ix, 390; 180 figs., 6 tables. New York, 1950 (Harper & Brothers, $4.50).—This book has been written for use in introductory courses in physics for non-science majors. It has been used by the authors in a course of this type at Yale University.

In the Introduction the authors make it clear that the book is neither intended for use in a survey-of-physics course nor in one which employs the historical or philosophical approach. Rather, it is suited to a course which seeks to cover in a fairly thorough manner "a portion (of physics) which can be constructed logically." Here the "physicist's concept of the atomic world" has been selected as such a portion, and it must be agreed that this choice is a happy one, since atomic physics constitutes a branch of physics which is simultaneously interesting, instructive, and significant.

The first half of the book develops the sections of mechanics, kinetic theory, electricity, and magnetism needed for an understanding of atomic and nuclear phenomena. Although the topics in this first half have been selected with great discrimination they still constitute a considerable portion which must be digested before the more delectable latter half of the book can be enjoyed.

The descriptions of atomic and nuclear phenomena which occupy the latter half of the book are frequently novel and are invariably lucid. It is evident that the authors have first-hand knowledge of their subjects and it is a pleasure to see these topics, which are so susceptible to exaggeration, treated with restraint.

At the end of each chapter there is a list of well chosen problems and a list of supplementary readings, while many physical constants which are pertinent to atomic physics are given in appendices. The book contains a very large number of specially prepared diagrams in which the principles to be illustrated are not masked by unnecessary detail.

The book is recommended to non-physicists as a means of self-education in the highly interesting subject of atomic physics and to instructors of science-for-the-non-scientist course as a persuasive description of this important branch of physics.

HENRY E. DUCKWORTH

The Identification of Molecular Spectra, 2d ed.; by R. W. B. PEARSE and A. G. GAYDON. Pp. xi, 276; 12 plates. New York, 1950 (John Wiley & Sons, Inc., $8.50).—Spectroscopy is now a much-used research tool in several of the sciences. Up-to-date tabulations of the principal wave lengths present in identified

atomic spectra and of the wave lengths of the band heads in known molecular spectra are indispensable to both experienced workers and to students who must interpret the usually complex array of lines in their spectrograms. Older spectroscopists can testify as to the great usefulness a quarter-century ago of Kayser's *Handbuch der Spektroscopie.* These tables by Pearse and Gaydon, which appeared in their first edition in 1941, now serve in much better style as an aid in the identification of the band spectra which often are the most conspicuous feature of a new spectrogram.

This second edition includes data published as recently as November, 1949. All recorded band systems of diatomic molecules are included, together with those of triatomic and more complex molecules which show well-defined band structure. Absorption spectra of complex organic molecules and of solutions are omitted. The wave-length range covered is from 10,000 A to 2,000 A.

There is first a table of persistent band heads arranged according to wave length. This is followed by the main section of the book, giving data for individual band systems in the alphabetical order of the chemical symbols of the molecules concerned. Next comes a useful section entitled "Practical Hints" and a set of twelve plates which include excellent photographs of many common molecular spectra and the usual comparison spectra. The main feature of the appendix is a table of persistent atomic lines.

These tables are organized in a most convenient manner and the format and printing are attractive. This is certainly an authoritative, valuable contribution to the literature of spectroscopy.

W. W. WATSON

Stratigraphy and Sedimentation; by W. C. KRUMBEIN and L. L. SLOSS. Pp. 507; 123 figs. San Francisco, 1951 (W. H. Freeman & Co., $5.00).—If sedimentation is the study of "the processes responsible for the formation of sedimentary rocks" and stratigraphy is the description and correlation and above all the interpretation of those rocks, in both their lithologic and biologic aspects, then the title of this book states its scope. After a chapter on stratigraphic classification, with emphasis on its growth, the book proceeds to the description of sedimentary rocks, processes, and environments, and to the principles governing lithologic and biologic distribution, *i.e.* facies. Correlation follows, and the last third of the book is devoted to the stepwise interpretation of the data, culminating in paleogeographic reconstruction as the basis for historical geology.

The level at which these subjects are covered is that of undergraduate seniors in geology, rather than advanced graduate students, but the treatment does not seem uniform, even at this level. The later interpretative part of the book is well and fully covered,

but the earlier descriptive part seems rather elementary, and it is handled mostly in cut-and-dried statements, as if the subject matter admitted of no argument or expansion. For example, the description of color is dismissed in a page without clear reference to the quantitative methods now available to geologists, though color is one of the neatest case examples of the great advances made possible by rigorously quantitative description of sedimentary properties. Likewise, in the description of particle size, Krumbein's elegant phi terminology is not used, though the present reviewer has found that intelligent seniors can readily grasp its real simplicity and superiority. Probably, however, the authors have preferred to conserve space for the later part of the book, and in any case they have supplied excellent bibliographies for each chapter, on the basis of which a teacher using the book can expand any topic he chooses.

In the later part of the book, moreover, the somewhat authoritarian tone is dropped, and subjects are presented so as to show the existence of controversy and the need for further work. This part of the book should excite students and indeed should also stimulate their elders. Krumbein and Sloss have been very active in the school of thought that emphasizes the importance of tectonics for stratigraphy (and for that matter the importance of stratigraphy for tectonics), but here they have integrated these newer views with the older environmental approach that received its "classical" expression in the *Treatise on Sedimentation* (1926, 1932). Also they have advanced without dogmatism new definitions and points of view for such fundamental concepts as facies and correlation, which are well worth the attention of all concerned with stratigraphy. With respect to correlation, for example, they cut loose from the conventional interpretation of correlation as time equivalence alone and advocate its use for biostratigraphic and rock equivalence as well; this view they have carried out consistently in their chapter on correlation. On this principle, a transgressive sandstone such as the Tapeats or the St. Peter would be said to correlate as a *rock* unit from one end to the other, though the two ends might not be equivalent in *time* at all. The reviewer for one finds this an undesirable extension of the accepted meaning of correlation and would point out that the authors themselves in their chapters on stratigraphic maps and paleogeography revert to the time-equivalent definition (pp. 394-395, 429-430). But the matter is worthy of explicit discussion by the profession.

One of the excellent features of the book is its insistence on data, preferably quantitative data, as a basis for stratigraphic interpretation. A fine chapter on stratigraphic procedures presents in detail the procedures for procuring these data from outcrop sections,

well cuttings, and mechanical well logs. (One misses however any reference to the data to be obtained by tracing and mapping units *between* sections, surely an integral part of stratigraphy.) Modern methods of presenting data are also stressed, and are beautifully exemplified in the many clear and well prepared diagrams throughout the book. The care in preparation and the thoughtful analysis that went into the book make it well suited as a text for an undergraduate course in sedimentary geology.

JOHN RODGERS

Pleistocene Terraces of the Susquehanna River, Pennsylvania; by Louis C. Peltier; Pennsylvania Geological Survey, 4th series, Bulletin G 23, Pp. x, 158; 49 figs., 46 tables. (Topographic and Geologic Survey, Department of Internal Affairs, Harrisburg, Pennsylvania, 1949).—In this bulletin the author has undertaken to shed light on the Pleistocene history of a river whose earlier history has long been in the forefront of Appalachian geomorphology. Detailed studies of terraces throughout the length of the main Susquehanna River and on the lower reaches of its tributaries—the Juniata, the West Branch of the Susquehanna, the North Branch of the Susquehanna, and the Chemung—have lead to an interpretation of the climatic history of the Pleistocene Epoch.

In a section on glacial geology, the lithology of deposits of the Binghamton and Olean substages of the Wisconsin stage, and of the deposits of the Illinoian stage is discussed; that of the Valley Heads and Mankato substages of the Wisconsin is given less attention. The pebble counts, used as a basis for differentiating the terraces, are not in themselves very convincing, but the following sections of the report, which deal with the differences in weathering, give strong support to the proposed ages of the valley fills.

The next part of the bulletin, probably the most important contribution, treats periglacial deposits. Eolian sand and loess are found in small quantity in the Susquehanna region, but of most significance is the rubble which Peltier recognized in both glaciated and unglaciated areas. Shale-fragment slopes, boulder-strewn slopes and blockfields are described, as are deposits of rubble occurring on different types of bedrock and on glacial drift. Photographs might have been used to advantage here. Although all captions are in their correct positions, figures 21, 24, and 27 were scrambled in the printing process.

A detailed discussion of the terraces along the various parts of the Susquehanna River system mentioned above follows. Three types of terraces, marginal kame terraces, frontal kame terraces,

and valley train terraces, are distinguished and can be correlated along the river. There are six main sets of them, representing, from younger to older, Mankato, Valley Heads, Binghamton, Olean, Late Illinoian and Illinoian (?) times. An interesting minor point, the change in the long profile of a terrace just below a knick-point caused by a change in the hydraulic gradient of the river, could have been treated more fully.

The last section is devoted to the author's hypothesis as to climatic conditions in Pennsylvania during the Pleistocene, and to changes therein as reflected by the history of the Susquehanna River. Each terrace is believed to represent a complete revolution in the river's regime, caused by changes in climate and in the load delivered by glacial action. The temperatures of the interstadials and their duration are reflected in the type of weathering of the deposits and in the depth of soil formation.

An excellent bibliography of 140 items appears at the end of the bulletin, and provides references on phenomena associated with periglacial regions, weathering, climate and previous work on the Susquehanna River region. Foreign (German) literature is well represented. Subject and geographic indices also appear.

Dr. Peltier's thesis is well worth study. Its shortcomings are mainly in organization. The reader should bear in mind that it was necessary for the author to cover an extensive area to collect his data and may have had little time for some of the details mentioned below. The idea that pre-Wisconsin deposits have been *rubified* (reddened) could have been treated at greater length; as a criterion of age it is almost too good to be true and may have a wider application than it has so far been given. The differences in depth of soil formation are discussed, and though they look convincing the author might have provided some statistical support, as most geologists are not very familiar with the techniques of soil scientists and tend to underrate their work. In describing rubbles, the author mentions the orientation of stones parallel to slopes; no diagrams of his fabric analyses are presented though they would have been of great interest to many of his readers. The bulletin does suffer from a lack of maps, those presented being diagrammatic. Although the several ages of the terraces are well established, nowhere in the text or figures is there any recognition of the existence of non-paired terraces, cut by lateral movement of the stream channel after rejuvenation. It is quite possible, though surprising, that none of these exist, and some explanation of this phenomenon might give his readers added confidence in Dr. Peltier's work.

JOHN A. ELSON

The Incomparable Valley: A Geological Interpretation of the Yosemite; by FRANÇOIS E. MATTHES, edited by FRITIOF FRYXELL. Pp. xv, 160; 11 figs., 50 plates. Berkeley and Los Angeles, 1950 (University of California Press, $3.75).—This volume is François Matthes' long-planned "Yosemite Book." It interprets in non-technical language the story of "the Sierra Nevada, the longest, the highest, and the grandest single mountain range in the United States," and the "Incomparable Valley" that lies at its heart.

For years Matthes had been writing and rewriting phrases, paragraphs, and pages for this book. Then, when his war-postponed retirement finally came, the long-awaited compilation was interrupted by his death. To Fritiof Fryxell, Professor of Geology at Augustana College, Illinois and the author of "The Tetons: Interpretation of a Mountain Landscape," was given the task of combining this voluminous, but scattered material into a unified book—Dr. Matthes' book.

Although written in simple language that requires no previous geological knowledge, the book will probably be enjoyed most by scientists and those interested in science. Forty-five excellent photographs, six paintings, and two diagrams are grouped at the front of the book. They illustrate many of the geological processes described in the book, but are not referred to in the text. Following these plates are 127 pages of delightfully descriptive text, which in story form describe the geographical setting and physical features of the Sierras, explain their origin, describe the Yosemite area, and tell the glacial history of Yosemite Valley. The final chapters break somewhat from the narrative style as they explain the origin of the tributary valleys, the waterfalls, and the colossal rock monuments that line the main valley, describe the latest effects of erosion and weathering in the valley, and chronicle the post-glacial climate changes.

Of special interest to geologists is Matthes' hypothesis that the Owens Valley country east of the Sierras was elevated with the Sierran block. The valley glaciers of the first Sierran glaciation (Glacier Point stage) advanced down broad, mature valleys graded to this elevated Owens Valley. Following this, the great scarp east of the Sierras was formed by the down-dropping of the Owens Valley block and the rejuvenated streams cut deep, youthful valleys in which the moraines of the last glaciation are found. The moraines of the first glaciation were left hanging high above in the remnants of the old mature valleys. As Matthes believes that the intensity of the first glaciation demands that the Sierras be at essentially their present altitude at that time, the Owens Valley block must have first been elevated, then down-dropped.

Unfortunately no attempt has been made to index this book, to list the illustrations, or in any other way to make the book easy to refer to. Had this been done, it would have made an excellent non-technical guide for the park visitor, as a large number of natural features, both in Yosemite Park and in the nearby parts of the Sierras, have been named and geologically described in the course of the story.

In summary, the "Incomparable Valley" is a geologically accurate narrative account of the geological history of the Sierra Nevada and of Yosemite Valley, as seen by François Matthes. Designed for the non-geological tourist, the trained geologist should find it interesting and relaxing reading.

DONALD H. KUPFER

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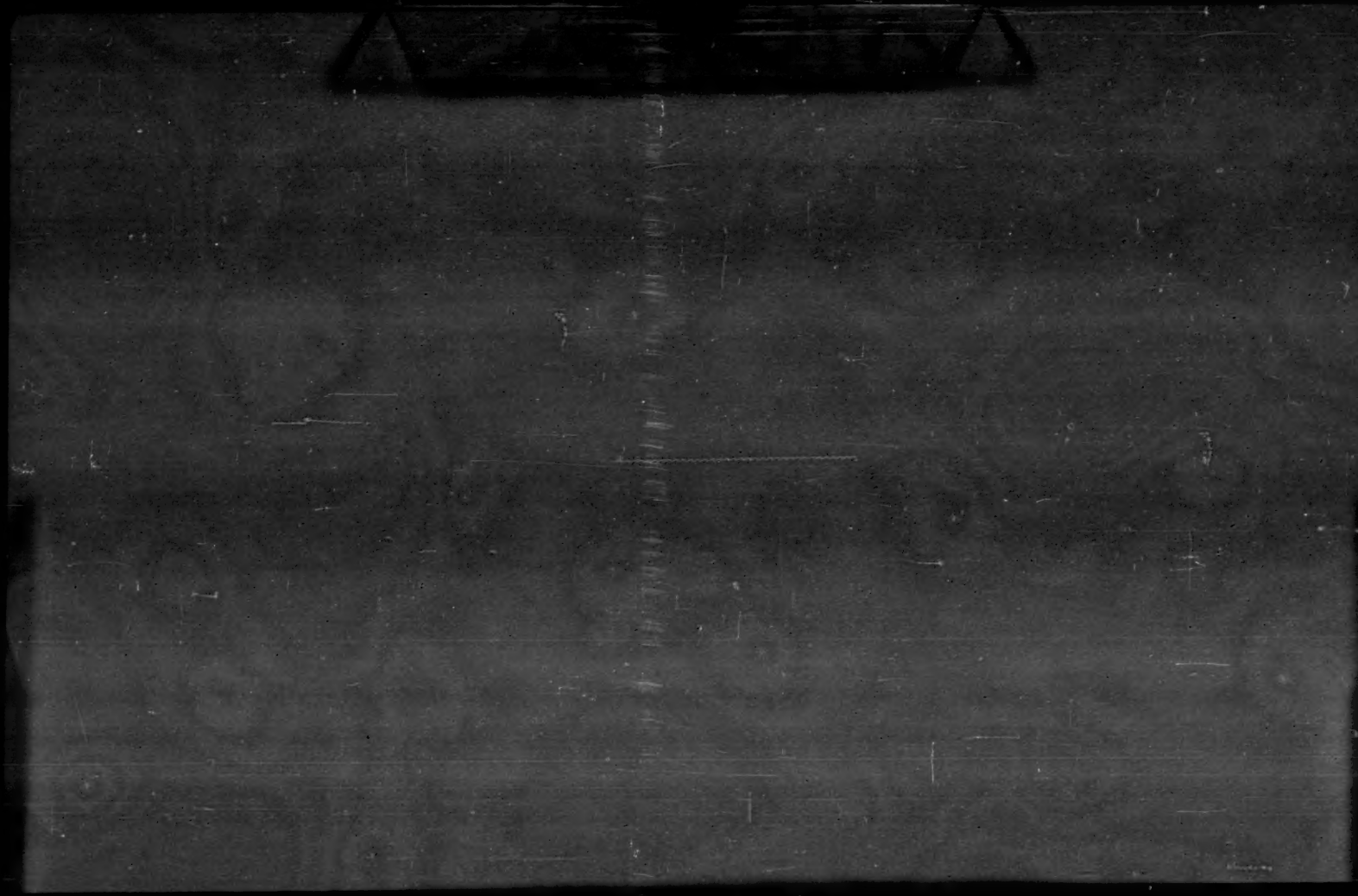

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